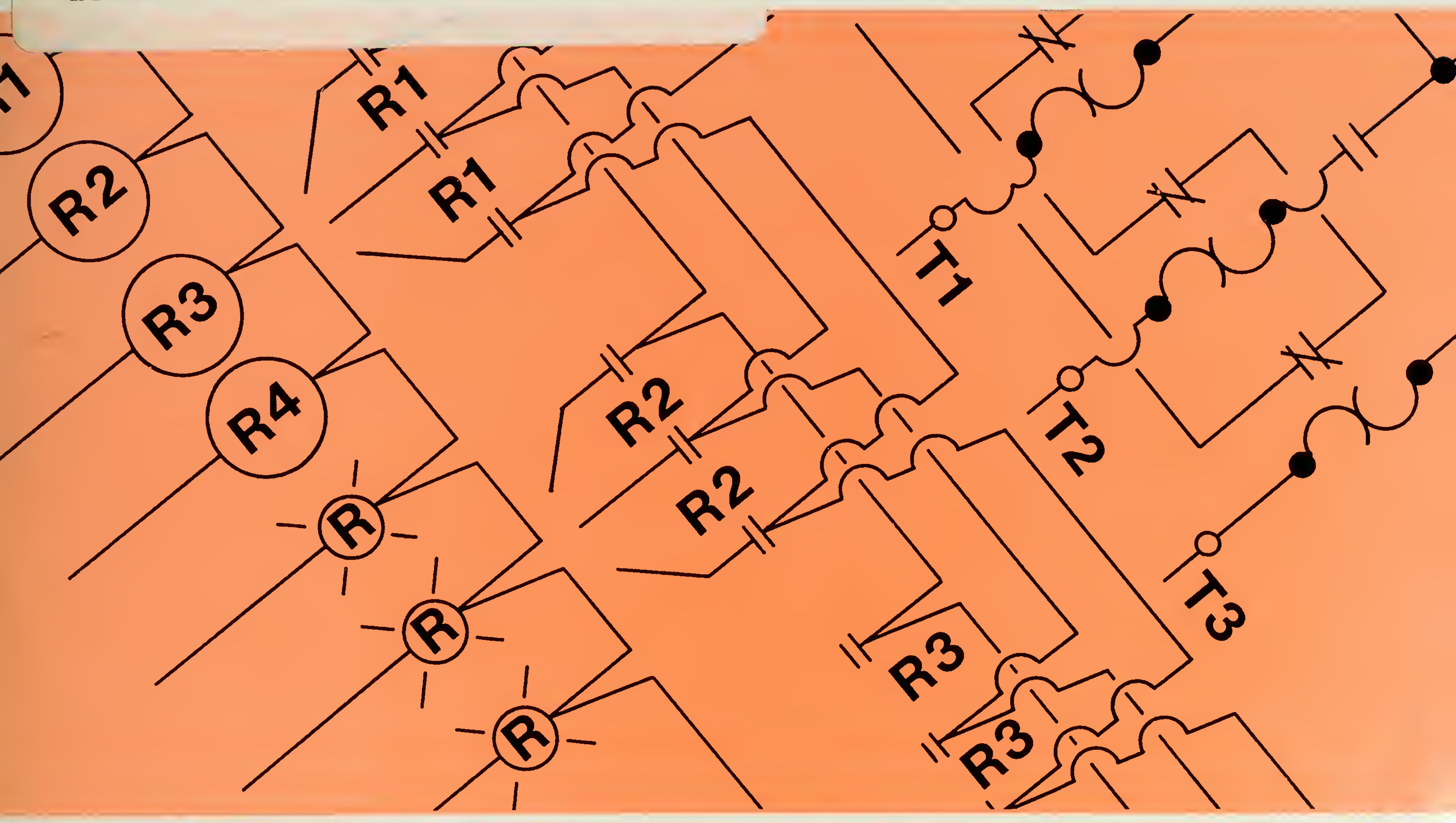
Agriculture Canada

Handling Agricultural Materials

Electrical controls and instrumentation



Canada

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Research Branch
Agriculture Canada

Publication 1840/E
1990

Cat. No. A15-1840/1990E
ISBN 0-660-13356-3
Printed 1990

Available in Canada through authorized bookstore agents and other bookstores or by mail from

Canadian Government Publishing Centre
Supply and Services Canada
Ottawa, Ont. Canada K1A 0S9

Price is subject to change without notice

Previously published under the title
Canadian Agricultural Materials Handling Manual. 5.1. Electrical Controls and Instrumentation.
Agric. Can. Publ. 5002.

Canadian Cataloguing in Publication Data

Handling agricultural materials. Electrical controls and instrumentation

(Publication ; 1840)

Previously published under title: Canadian agricultural materials handling manual. 5.1. Electrical controls and instrumentation.
Issued also in French under title: Manutention de produits agricoles, instruments et appareils de régulation électrique.
"Prepared by UMA Engineering Ltd."–Foreword.
Includes bibliographical references.
Cat. No. A15-1840/1990E
0-660-13356-3

1. Electric controllers. 2. Electric current converters.
3. Agricultural machinery–Electric equipment.
I. Rudnitski, Sharon. II. Birenbaum, Rhonda.
III. Heslop, L. IV. UMA Engineering Ltd.
V. Canada. Agriculture Canada. Research Branch. VI. Series: Publication (Canada. Agriculture Canada). English ; 1840.

TK2796.H3 1990 621.31'042E20 C89-099212-6

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FOREWORD

Handling Agricultural Materials is produced in several parts as a guide to designers of materials-handling systems for farm and associated industries. Sections deal with selection and design of specific types of equipment for materials handling and processing. Items may be required to function independently or as components of a system. The design of a complete system may require information from several sections of the manual.

This section was prepared by UMA Engineering Ltd., Winnipeg, Man., for the Canada Committee on Agricultural Engineering Services of the Canadian Agricultural Services Coordinating Committee.

1 TERMS AND DEFINITIONS

A well-designed, well-implemented control system integrates the control instruments with the mechanical equipment to be controlled and with the human operator of the system. These three aspects of the system interact to such a degree that neglecting any element reduces the system's ability to control the operation for which it is designed.

This book describes some of the practical aspects of control system design, as well as the pitfalls to be avoided. Designers must understand the process to be controlled, the limitations of the mechanical equipment involved, the methods for measuring the process variables, and the system operators' needs. For more information, consult the publications listed in the references.

The language of control system design includes several important terms. They are defined here.

1.1 Contacts

A part of a relay, switch, or connector, the contact carries current through an electrical circuit. It engages or disengages to open or close the circuit.

1.2 *Normally open contacts* Normally open contacts do not conduct electrical current in their nonactuated position.

1.3 *Normally closed contacts* Normally closed contacts conduct electrical current in their nonactuated position.

1.4 *Momentary contacts* A momentary contact, which can be either normally open or normally closed, is actuated by an outside force. Outside forces include relay contacts, push buttons, or selector switches with spring return actions.

1.5 *Maintained contacts* A maintained contact remains in its last state (either closed or open) until an outside force acts on it. Examples include manual light switches or latch relays.

1.6 Relays

A relay is an electromagnetic device in which contacts open or close according to variations in subtending electric circuits. The state of the relay, in turn, affects the operation of other devices in the electric circuit. The contacts of a relay are considered momentary because their action depends on whether the relay coil is energized or de-energized.

1.7 *Timing relays* Timing relays operate contacts after a preset time elapses.

1.8 *Latch relays* A relay with contacts that change position when the relay is energized and remain in the changed condition even though the relay coil de-energizes is called a latch relay. Latch relays have a second coil, the reset coil, which later unlatches the relay contacts.

1.9 *Sequence relays* A sequence relay controls two or more sets of contacts in a predetermined sequence. Alternately energizing and de-energizing the sequence relay coil, stepping it from one phase in the sequence to the next, controls the relay. Typically, sequence relay contacts remain in the relay's current stage until stepped to the next sequence phase.

1.10 Contactors

A contactor is a relay or switch with high-current contacts.

1.11 Overloads

Overloads protect motors from excessive current during operation. They allow a large current to pass for a short period of time when motors start; at this time high inrush currents are typical. However, if a high current persists the overload interrupts the energy supply to the motor. Overloads can be reset either automatically or, more commonly, manually.

1.12 Motor starters

A motor starter is a contact set with integral overload protection. Starters can be either manual or electromagnetic. In manual starters the overload protection mechanically disconnects the power supply to the motor. In electromagnetic starters, the overloads disconnect the current to the coil that supplies energy to the motor.

1.13 Digital control systems

If the signals into and out of the controller can occur in only two different states—either two voltage levels or two current levels—the system is called a digital control system.

1.14 Analog control systems

Continuous variable signals into and out of the controller characterize analog control systems. Analog signals vary widely, for example between 4 and 20 mA or between 1 and 5 V.

1.15 **Input signals**

The current, voltage, power, or other driving force applied to a circuit or device are considered input signals. Input signals can be either digital or analog.

1.16 **Output signals**

Output signals are the current, voltage, power, or driving force delivered by a circuit or device. Output signals from control systems operate end devices such as indicators, motors, or valves. Like input signals, output signals can be either digital or analog.

1.17 **Logic**

In control systems, logic refers to the plan that defines the interactions of signals in an automatic data-processing system.

1.18 **Algorithm**

The algorithm is a set of rules for solving a problem in a finite number of steps. For example, a full statement of an arithmetic procedure for finding the valve position required to achieve a particular flow is that system's algorithm.

1.19 **Programmable controller**

Programmable controllers replace conventional relays, timers, and sequencers in digital control and, more recently, analog control systems. The programmable controller emulates conventional relay logic.

1.20 **Software and hardware**

The logic and algorithms used in programmable controllers constitute the software. The hardware comprises the control system equipment, including all the movable and nonmovable parts.

1.21 **End devices**

The end device, or final control element, connects to the input or output of a controller or control system.

1.22 **Controlled variables**

The controlled variables respond to control by the end devices. End devices typically measure or control such variables as temperature, pressure, or flow.

1.23 **Throttling range**

The throttling range is the amount of change in the controlled variable required to move the end device actuator from one extreme to the other.

1.24 **Set point**

The set point is a controller setting that specifies the desired value of the controlled variable.

1.25 **Control point**

The control point is the actual value of the controlled variable. If the control point lies within the throttling range of the controller, it is said to be in control. When the control point exceeds the throttling range, it is said to be out of control.

1.26 **Offset**

Offset is the difference between the set point and the control point. It may also be called control point shift, drift, droop, or deviation.

1.27 **Stability**

Stability refers to the ability of a control system to maintain the controlled variable at or near the set point without requiring the controller to change continuously from one extreme to the other.

1.28 **Electrical codes**

Local electrical inspection authorities voluntarily adopt and enforce the *Canadian Electrical Code* (CEC). In addition to the CEC, individual provinces and local inspection agencies often require that equipment meets special conditions. Most local authorities use the standards of the Canadian Standards Association (CSA). Reputable manufacturers of control equipment generally obtain CSA approval for their products.

All the various electrical codes aim to establish safety standards for the installation and maintenance of electrical equipment. Take care when selecting and specifying equipment to ensure it meets all the requirements of the local codes and the CEC. And, if possible, select equipment approved by the CSA for the application.

Designing systems for hazardous locations demands particular attention to the appropriate electrical codes and standards. The CEC describes hazardous locations this way:

Areas in which there exists the hazard of fire or explosion due to the fact that:

1. *Highly flammable gases, flammable volatile liquids, mixtures or other highly flammable substances are manufactured or used, or are stored in other than original containers,*
2. *Combustible dust is likely to be present in quantities sufficient to produce an explosive or combustible mixture, or where it is impracticable to prevent such dust from collecting in or upon motors or other electrical equipment in such quantities as to produce overheating through normal radiation being prevented, or from being deposited upon incandescent lamps,*
3. *Easily ignitible fibres or materials producing combustible dusts are manufactured, handled, or used in a free open state, or*
4. *Easily ignitible fibres or materials producing combustible dusts are stored in bales or containers but are not manufactured or handled in a free open state.*

1.29 Enclosure definitions

The following information defines the various categories of electrical equipment enclosures, as specified by the Canadian Electrical Manufacturer's Association (CEMA). This listing also describes the appropriate environment (according to the CEC) for each enclosure.

1.30 *CEMA Type 1* This is a general-purpose enclosure. Use it for indoor applications in normal atmospheres.

1.31 *CEMA Types 4–9* Use these enclosures for locations requiring watertight apparatus. They also suit coal or flour mills, and other locations generating hazardous dust. The enclosures are made of stainless steel with a synthetic rubber gasket sealing the cover.

1.32 CEMA Type 4 Use these enclosures in dairies, food-processing plants, breweries, tanneries, pump houses, outdoor locations, or other areas subjected to splashing water or a great deal of moisture. A gasket seals the cover.

1.33 *CEMA Type 4X* Made of glass-reinforced polyester, this type of enclosure is both watertight and corrosion-resistant. A synthetic rubber gasket between the cover and base provides an effective seal. Industries such as chemical plants and paper mills rely on type 4X enclosures.

1.34 *CEMA Types 5 and 12* Use these enclosures in metal-working plants and other industrial applications or hazardous locations. The cover seals with a synthetic rubber gasket, preventing the entrance of splashing oil, coolants, metal chips, dirt, or lint.

1.35 *CEMA Type 7* For locations subject to hazardous gas, these enclosures are made of cast and bolted metal. This type of enclosure meets requirements of the CEC for Class I, Groups C and D locations. A wide, machined flange inserts between the cover and base.

1.36 *CEMA Type 13* Oil and dust tight, these enclosures protect against spraying water, oil, or coolant. They are also impervious to seepage or external condensation. Use them indoors primarily for pilot devices such as limit switches, push buttons, selector switches, or pilot lights.

1.37 Guidelines for selecting equipment

Use these guidelines to select control equipment:

- application
- Canadian Standards Association ratings
- availability
- support
- performance

1.38 *Application* Most manufacturers of industrial control equipment offer complete lines of control components in a variety of sizes, shapes, and enclosures. Obtain catalogs from the various manufacturers and select the appropriate devices from the wide array available. Rely on the manufacturers' recommendations, and observe the design and safety criteria.

1.39 *Canadian Standards Association ratings* Pay close attention to CSA approval ratings to ensure the selected equipment actually suits the application. For example, a switch or sensor may be approved for use in nonhazardous areas but is inappropriate for areas plagued by grain dust.

1.40 *Availability* Some equipment, although suitable for the application, is not readily available. Specialty devices such as speed sensors, humidity sensors, ultrasonic level sensors, and electronic controllers fall into this category since they cannot be easily replaced with those of another manufacturer.

1.41 *Support* Do not use specialized control equipment unless technical support is available to maintenance personnel. In most areas, at least some equipment suppliers offer such support, select equipment from them.

1.42 *Performance* Before selecting a particular piece of equipment, contact current users to assess the performance of the equipment. Check, too, on users' satisfaction with the supplier and manufacturer. Testimonials like these save much grief.

1.43 Circuit types

In general, process control systems rely on six basic circuit types:

- digital, or on–off, circuits
- timed digital circuits
- floating-action circuits
- proportional-action circuits
- proportional-action circuits with automatic reset
- proportional-action circuits with reset and derivative

Digital-action, timed digital-action, and floating-action circuits rely on electromechanical control equipment. Proportional action circuits control analog electromechanical systems. The other circuits operate with electronic analog control equipment. Programmable logic controllers can perform all of the control functions listed.

1.44 *Digital circuits* Digital (or on–off) control usually involves turning on or off various components of the process. Gates, valves, conveyors, augers, or heaters typically operate this way. Contact closures (or openings) from various switches and relays generate inputs to the control system. Automatic timers, measurable aspects of the process (e.g. full or empty hoppers, maximum or minimum temperatures), or human operators control the contacts.

Use ladder diagrams to develop the control programs for on–off processes. These diagrams show each component in the process and the conditions that cause the components to connect to the power source. Section 8.2 discusses ladder diagrams in detail.

1.45 *Timed digital circuits* These circuits reduce the operating differential by artificially shortening the on or off times in anticipation of a system response. For example, a heating thermostat may include a small internal heater that energizes during on periods, thereby giving a false signal to the thermostat. The internal heater turns off the thermostat before the system temperature stabilizes to the preset value. The heater cycles this way to avoid localized overheating or because calculations indicate the system itself will stabilize to the correct temperature shortly after the thermostat switches off. This process is called heat anticipation.

1.46 *Floating-action circuits* Floating-action circuits can stop and reverse at any point in their control range. A dead spot or neutral zone in the controller sends no signal and allows the device to float in a partly open position. For good operation, however, a system with this kind of circuit must respond rapidly to the controlled variable; otherwise it cannot stop at an intermediate point.

An engine-driven system that controls pump discharge pressure using a reversing motor-driven throttle and two pressure-actuated switches operates with floating-action circuits. The high-pressure switch drives the motor in reverse and the low-pressure switch drives the motor forward. There is a dead zone between settings on the high- and low-pressure switches.

1.47 *Proportional-action circuits* Proportional-action circuits add feedback to the floating-action configuration. Feedback ensures the controlled device actuator moves only enough to satisfy the change in the controlled variable. The controlled variable need not respond.

Use this type of control circuit in applications such as level control, where the controlled variable responds relatively slowly.

The term modulating control may also refer to proportional control. Strictly speaking, though, floating control also modulates.

1.48 *Proportional-action circuits with automatic reset* A proportional-action circuit with automatic reset, also called proportional plus integral or lag compensator, automatically returns the control point to the original set point whenever any offset occurs. The automatic reset effect increases the gain of the controller as the rate of change in the control point increases. This action accelerates the return of the control point to the original set point and controls the controlled variable more accurately than do other circuits. A wide throttling range provides added stability to the system.

1.49 *Proportional-action circuits with reset and derivative* The addition of derivative to a proportional-action circuit allows the rate of set point correction to equal the rate of change in error. Use this type of control in systems where the inertia of the process interferes with accurate control.

A liquid tank with level control, variable-input control, and variable output, for example, can benefit from a proportional-action circuit with reset and derivative. This kind of circuit allows the liquid input rate to increase as the liquid level moves farther from the level control point.

2 LOGIC CIRCUIT COMPONENTS AND CONTROLS

Logic circuits use control components to determine whether or not an event has occurred. These components respond to either the system's human operator or to changes in the controlled process.

2.1 Push buttons and selector switches

Push buttons and selector switches, manual devices that the system operator controls, modify the control action. Depending on the logic requirements, the buttons and switches can be either maintained, momentary, normally open, normally closed, or a combination of these functions. Buttons and switches operate from the controlled device, a central control station, or both.

2.2 Limit-position sensors and switches

Limit-position switches provide inputs to digital control systems. They supply information regarding the position of gates, valves, and other mechanical equipment. And, depending on the logic, these switches enable or inhibit the system.

Typically, these switches indicate only one of two possible states of the controlled device: whether the device is fully open or fully closed. If the control system must receive information on both open and closed states, use multiple switches. Control diagrams should illustrate the control action of limit switches. For example, the diagram would show that the switch closes when the gate opens.

2.3 Pressure sensors and switches

Pressure switches connect directly to the process circuitry and respond to preset pressures. There are two types of pressure switches:

- fixed-differential
- adjustable-differential

Fixed-differential switches operate at particular pressure settings. On sensing the set pressure, the switch contacts change from one state to another, for example, from open to closed. The point at which the switch returns to the original state depends on the factory setting of the differential pressure. Usually, this setting lies within a small margin.

Adjustable-differential switches adjust to operate at different pressures and pressure differentials. This type of pressure switch changes state and reverts to normal in response to different user-determined pressures.

Pressure switches open or close with rising or falling pressure. With adjustable-differential switches, both the rising and the falling pressure settings must be determined and the switch adjusted accordingly. Logic diagrams illustrate both these control actions. For example, the diagram could specify that the switch closes when the rising pressure reaches 350 kPa.

Pressure switches function in two different capacities. They can control a process directly, as in the case of a well-pump control system or air compressor. Or they can act as input signals to a control system for logic control to provide safety shutdown in the event of high or low pressure.

2.4 Proximity sensors and switches

Generally, proximity switches apply to the same functions as limit-position switches. The newer designs of these noncontacting proximity switches can sense the position of gates or valves without any mechanical connection. These types of switches suit hostile environments.

2.5 Level sensors and switches

Level sensors respond to the level of liquids or solids in a tank and actuate switches to maintain the level within preset limits. The sensors and switches may be contact or noncontact devices.

The various types of level switches and sensors can be divided into two groups:

- liquid-level
- material

In all cases, show on the logic diagrams the operating points and control actions for each. For example, the diagram would specify that the switch closes at 2 m on rising level.

There are four types of liquid-level sensors and switches:

- tilt
- float
- conductivity
- ultrasonic

Material-level switches determine the depth of solids, such as grain, in storage bins. The most common types are:

- diaphragm
- torque
- ultrasonic

A description of both liquid- and material-level switches and sensors follows.

2.6 *Tilt switches* This type of level switch typically consists of a mercury bulb mounted inside a plastic housing. When the liquid level rises above the switch, the housing tilts thus making (or breaking) an electrical circuit. Inherent in their design, tilt switches respond to very small changes in liquid level. As a result, control circuits require at least two such switches.

Tilt switches heavier than the liquid being measured need only be hung by the electrical cord at the correct elevation. Lighter switches require fastening at the desired position.

2.7 *Float switches* Two collars affixed to a rod that is attached to a float makes up the most common type of float switch. As the liquid level rises, the rod moves up. When the lower collar on the rod reaches the switch mechanism, the rod transfers the switch contacts. When the liquid level falls to where the upper collar reaches the switch, the contacts revert to the original position.

Another type of float switch uses a system of pulleys and counter weights to operate mercury switches mounted on a rotating shaft. These types of switches suit applications that require multiple switch points and adjustable differentials.

2.8 *Conductivity switches* Conductivity switches operate by exposing two electrode probes, usually mounted at different elevations, to the liquid. When the liquid surrounds both probes, the switch contacts change state. Operating differential can be achieved with most conductivity switches through the use of multiple probes. For example, exposure of a second probe in a liquid-level tank could change a two-speed pump from low to high speed to increase the refill rate.

Do not use conductivity switches in applications where nonconductive materials, such as grease or oil, could build up on the electrodes.

2.9 *Ultrasonic switches* Ultrasonic level switches use a time delay to determine the liquid level. The time for an ultrasonic pulse to leave a transducer, strike the liquid, and return to the transducer correlates to the liquid's level. Most ultrasonic level switches have multiple switch points and some have complete pump-control logic (with multiple pump operation) integral with the electronic controls.

Use ultrasonic switches in difficult level-control applications or in hazardous locations, for example to measure sewage, viscous liquids, or slurry levels.

Dust interferes with reliable operation of some ultrasonic material switches. Consult the manufacturer before selecting ultrasonic switches for dusty applications.

2.10 *Diaphragm switches* Diaphragm switches mount into bin walls and sense the pressure of material against the diaphragm. The movement of the diaphragm operates a switch located outside the bin.

2.11 *Torque switches* A torque switch consists of a motor-driven paddle mounted on the bin wall. When the material surrounds the paddle, the paddle stops rotating, thus actuating an externally mounted torque switch. Use multiple torque switches if differential action is required; for example, use them to vary the input or output rates rather than simply to turn input or output devices on or off.

2.12 Temperature switches

Temperature switches respond to the temperature of a specific location in a system. In addition, they actuate switches to maintain a temperature setting, or series of settings, within preset limits.

Temperature switches require that their operating points be identified on logic diagrams in the same way as level and pressure switches are specified.

2.13 *Bimetal switches* Bimetal switches consist of two different metal strips, each with a unique temperature coefficient, bonded together. As the temperature changes, the bimetal strip bends and applies a force to a switch mechanism.

These switches are inexpensive and are often found in heating and ventilation applications.

2.14 *Capillary bulb switches* In capillary bulb switches increasing temperature causes the expansion of a liquid in a sealed chamber. The expanding liquid applies a force to a piston which, in turn, operates a switch.

Generally a single enclosure houses both the switch and the capillary system. Alternatively, the switch mounts separately with variable lengths of capillary tubing connecting it to the temperature-sensing bulb. Remote capillary sensors measure the temperature at one point; or they average temperature over a

length of capillary tubing. Use a capillary bulb switch that measures averages in applications where the temperature may not be uniform throughout, for example in air ducts.

Capillary temperature switches are available with fixed- and adjustable-differential switch settings.

2.15 Relays

Most commonly, relays provide electromechanical control systems with decision-making capabilities by forming logic circuit connections. Additionally, relays replace switches to control power at remote locations and to control high-voltage or high-current devices with a low-voltage, low-current switch.

Relays come in a variety of coil voltages and contact current ratings. Some relays are available with as many as eight contacts, which may be normally closed, normally open, or some combination of both. Convertible contact relays, also available in most industrial grades, do not have fixed contact positions and can change from normally open to normally closed (and reverse). This feature is useful should the system require logic changes after installation.

Sockets with plug-in relays suit applications expected to require frequent replacement of relays, for example, in frequent cycling applications. Use this sort of relay, as well, where low cost is an important factor in design.

Some industrial-grade control relays are available with hermetically sealed contacts. Called reed relays, they switch very low voltage or current loads. Use them in hazardous areas.

2.16 *Latching relays* Use latching relays in applications where the relay state must be retained during a power failure or after a momentary event. For example, a latching relay may operate in tandem with a high-discharge pressure shutdown switch on a pump. The pressure switch stops the pump by momentarily energizing the latching relay. This action interrupts the motor starter coil current. After the pump stops, the discharge pressure drops, but the latch relay prevents the pump from restarting until the operator resets the latch relay.

Latching relays latch either magnetically or mechanically. Most have two coils, one to latch and the other to unlatch the contacts. Adding latching attachments to industrial-grade control relays converts them to latch relays.

2.17 *Timing relays* Timing relays operate either 'on delay' or 'off delay.' For 'on delay' the relay contacts operate at a set time after energizing. The contacts of an 'on-delay' relay are denoted as either normally open time to close (NOTC) or normally closed time to open (NCTO).

In 'off-delay' mode the relay contacts operate at a set time after de-energizing. The contacts of the off-delay relay are denoted as either normally open time to open (NOTO) or normally closed time to close (NCTC).

The flow of a fluid from a spring-loaded bellows through an adjustable needle valve commonly controls the relay timing function mechanically. Alternatively, an electronic circuit achieves the same function.

Attachments are available to convert industrial-grade control relays to timing relays.

2.18 *Sequencers* Sequencers, or stepping relays, apply in control systems where a predetermined series of actions takes place, one after another. An automatic restart system operating a group of large motors represents such a system. The high inrush current of starting motors prevents them from starting simultaneously. A stepping relay operated by a timing relay starts each motor in turn, with a time delay between steps.

Some sequencers are bidirectional, having two coils: one to step up and one to step down.

2.19 Electromechanical controls

An electromechanical control system consists of sensors, selector switches, relays, timers, and sequencers connected together according to a logic diagram. Based on this diagram and on the input signals to the system, the electromechanical controls operate end devices such as motors, valves, and gates. Digital signals generally furnish the inputs and outputs to modern electromechanical control systems.

2.20 Analog controllers

Choose analog or modulating controllers for applications requiring smooth or continuous control. Essentially there are two categories of analog control systems: electromechanical and electronic.

2.21 *Electromechanical analog controllers* Electromechanical analog controllers most commonly control pressure, temperature, and humidity in commercial heating and ventilation systems. However, they also suit other applications with simple control requirements. These controllers are widely available, low cost, and easy to maintain.

The controller consists of a variable potentiometer that responds to changes in the controlled medium. Process changes (e.g. rising temperature) cause a corresponding change in fluid pressure in a bulb and capillary. Bellows transmit this change to a lever arrangement that moves the sliding contact on the potentiometer.

The controlled device is usually a motor-driven gear train with an output shaft that rotates up to 160°. This shaft connects to valves, gates, or dampers either directly or, more often, through a series of linkages. The motor is reversible and includes a balance relay and a feedback potentiometer. A set of contacts on the balance relay starts, stops, and reverses the motor. The balance relay operates the motor until the resistance signal from the controller equals that from the internal feedback potentiometer.

Manually operated potentiometers inserted into the controller output signal allow for manual override of the motor. They also limit the travel of the motor. One controller can regulate several motors by using an auxiliary potentiometer in one of the motors.

2.22 *Electronic analog controllers* Electronic analog controllers differ from their electromechanical counterparts in two ways. Electronic controllers have more sophisticated control capabilities and they operate on different control signals. Electronic controllers first convert the process variables (e.g. temperature) to an electronic signal, which the analog controller then uses as a basis for control decisions.

The standard analog control signal is a current of 4–20 mA; 4 mA represents the lowest value of the process variable and 20 mA represents the highest. When many instruments use the same process signal as an input, the current of 4–20 mA is supplied to a 250-ohm precision resistor to convert the signal to 1–5 V. This second signal is also an industry standard for use in control panels where the limited length of the wires does not affect the signal.

The output signal from the controller is also 4–20 mA. This signal operates the final control element through its full range of operation. Some final control elements, such as variable-speed motor drives and motorized valves, accept the signal of 4–20 mA directly. Others require an interface to convert the milliampere signal to some other variable. Air-operated valves, for example, operate through their range with an air pressure of 20–120 kPa. A current-to-pneumatic converter, or I/P, converts the output signal in this example. Other interfaces available convert signals of 4–20 mA to voltage, hydraulic pressure, frequency, or current.

Unlike electromechanical controls, electronic control systems require special wiring and installation. Use the following guidelines to minimize the impact of electrical interference on the optimal operation of electronic equipment. However, if a system involves more than one or two analog control functions, consult the industrial instrumentation literature for more detailed information.

- Ensure all wiring conforms to the *Canadian Electrical Code* or the best commercial practice as determined by local electrical codes.
- For cables carrying analog signals, use twisted pair wiring with an overall copper foil shield or conductive coated mylar shield with drain wire.
- Keep signal cables physically separate from alternating current (AC) power and control wiring by at least 200 mm.
- Have signal and AC power bundles cross each other at right angles.
- Ground shielded wire at one end only, preferably at the control room.

2.23 Programmable logic controllers

A programmable logic controller (PLC) is a control system capable of being set (programmed) to operate in a specified manner. It uses mathematics (logic) to deal with relationships among conditions or events and to produce a prescribed and changeable output.

Use PLCs, now available in a wide variety of sizes, in place of conventional electromechanical equipment for all but the smallest control systems. Most PLCs are programmed in standard ladder logic form and directly replace conventional equipment. All PLCs include relays, latch relays, timing relays, counters, and sequencers as standard features. In addition, many PLCs have extensive analog control capabilities as well as mathematical functions. Entire control systems can rely on these devices.

Some PLCs can also communicate with remote computer systems or even other PLCs. Large control systems, such as grain elevators, may benefit from this capability, adding information for accounting or management purposes to the overall system.

PLCs are designed to withstand rough handling, to operate in temperatures from 0°C to 60°C, and to function in environments of high electrical noise. However, some machines are not able to operate reliably in environments where brown-outs (episodes of sustained low-power-supply voltage) or harmonics occur on the power supply lines. These conditions

often occur in rural applications, particularly where phase converters or large motors operate. Ensure that PLC equipment selected for use in these noisy electrical environments has a proven track record.

Five important components make up programmable controllers:

- central processing unit
- memory
- input signals
- output signals
- programmer

2.24 *Central processing unit (CPU)* The CPU acts as the brain of the controller. Here the PLC interprets and executes the program.

In executing the program, the processor examines all the inputs to the system to establish their status. For digital inputs, it assesses whether they are on or off. In the case of analog inputs, the CPU determines the value of the process variable or variables. It then operates the outputs from the controller according to the logic in the program.

This program activity repeats, starting from the top of the ladder diagram and continuing to the bottom, as long as the controller operates. The frequency at which the program is repeated is called the scan time. Scan times can vary from 1 to 200 ms, depending on the type of controller and the size of the program. In applications requiring fast response to external events, for example material-packaging equipment, scan time is critical. However, in most control systems the slower scan time of 200 ms presents no problems.

2.25 *Memory* The PLC holds different sizes of programs, depending on the amount of memory in the controller. Memory size is referred to as K with each K representing 1024 words of memory. Some PLCs use words with more information in them than others. Therefore an 8K machine of one type may not have any more program storage than another machine designated 4K. Also, some types of PLCs use memory more efficiently, often depending on the ratio of calculations to logic in the program. Note, too, that a PLC with 32K of memory is considered to be very large. Compare this fact to personal computers where a machine with 32K of memory would be small.

In most PLCs, memory expansion is expensive if not impossible beyond a certain point. All manufacturers market various sizes of controllers. Take care to select a controller that contains enough memory to satisfy the control system needs.

2.26 *Input signals* Input signals are grouped into units, called modules, of multiples of 4 up to 32 input signals each. The input modules generally plug into racks which, in turn, attach to the CPU. Programmable controllers can handle both digital and analog input signals.

The controller accepts a variety of digital voltage input signals of either AC or direct current (DC). As well, the input signals may be isolated or nonisolated. Isolated input signals connect the controller to individual voltage sources such as motor starters. Nonisolated input signals utilize a common voltage source for several signals.

Several analog input signals provide information to the controller. These signals include voltage (1–5 V), current (4–20 mA), and direct data from thermocouples for temperature measurement.

2.27 *Output signals* Output signals organize in the same modular fashion as the inputs. And as with input, output signals are either isolated or nonisolated.

Only solid-state or relay contacts can generate output signals from the programmable controller. Output voltage signals from 5 to 230 V (AC or DC) are available. Analog output signals are usually configured to produce a current signal of 4–20 mA.

2.28 *Programmer* The programmer is a portable tool used to insert the program into the CPU. Programmers for large PLCs include computer keyboards and full-size video display screens. Small PLCs rely on calculator-style keyboards with liquid-crystal display (LCD) screens.

Most PLC manufacturers now offer software that allows standard personal computers to act as programmers. This option is gaining popularity as personal computers increase in availability and decrease in cost. As well, personal computers serve many functions beyond simple PLC programming, whereas the dedicated programmer has no other use.

2.29 Software

Although all programmable controllers attempt to emulate electromechanical controls, different systems, even those of the same manufacturer, achieve this function in various ways. The use of latching relays illustrates one example of how PLCs differ. One manufacturer uses a two-coil relay (latch and reset) whereas another uses only a single coil. After a power failure, the two-coil latch relay behaves exactly the same as its electromechanical counterpart; the single-coil relay remains latched only for the first scan of the controller after restoration of power.

The way in which logic is solved demonstrates another example of the differences among PLCs. Some systems separate the ladder diagram program into networks and then solve the logic network by network, from the beginning of the program to the end. Other PLCs arrange ladder logic in a continuous series of rungs, not using the networks approach at all. Different controllers also handle mathematical functions differently.

Individuals designing software for PLCs must understand system variances. Test each control function with a demonstration circuit to establish that the equipment operates as expected.

2.30 Documentation

PLCs maintain, in memory, a record of the logic program as well as any changes made to the program. This information can be reproduced at any time on a printer.

A further enhancement of the usual logic printout is an annotated listing of the program. This listing details the program logic along with textual descriptions of what the logic does. It also includes a listing of where, in the program, the logic is acted on.

3 PROCESS MEASUREMENT

Correctly selecting equipment for process measurement depends on clearly defining three important factors:

- the measurement objective
- the expected measurement range
- the normal and abnormal physical qualities of the substance being measured, including pressure, temperature, corrosiveness, interfering constituents, and hazardous characteristics

These same three criteria also aid in determining the level of accuracy, response, repeatability, and reliability required by the process application.

Select appropriate measurement devices only after defining the application. Then, when making a selection, be sure to understand the fundamental operating principles of the devices available for that application.

Almost all process variables can be measured and converted to a 4–20 mA signal. Use this analog signal to determine, for example, switch points controlling motors, valves, gates, and alarm circuits.

Conventional control systems achieve process measurement with an analog switch that operates contacts at predetermined set points. Programmed appropriately, programmable controllers accept the analog signal and operate output devices based on the analog value. For example, temperature sensor output can either connect to analog switches or to programmable controller analog input modules.

Instrumentation suppliers offer a wide array of process measurement devices. Most suppliers provide comprehensive catalog material to streamline equipment selection.

3.1 Level-measurement devices

Choose from contact or noncontact level measurement devices. Contact level instruments include mechanical float systems, capacitance probes, pressure (or head) transmitters, and transmitters actuated by displacement. Ultrasonic transmitters, bubbler systems, and weight transmitters provide noncontact measurement.

Use ultrasonic devices to measure the level of solids. Or use weight as an indirect measurement of the solids level if the particle size of the material is uniform and the moisture content constant.

Common problems associated with level measurement include surface turbulence, liquid viscosity, or dust which is especially a problem with ultrasonic devices.

3.2 Flow meters

There are eight common types of flow meters:

- head flow meters
- electromagnetic flow meters
- velocity flow meters
- volumetric flow meters
- ultrasonic flow meters
- vortex-shedding flow meters
- force-displacement flow meters
- mass flow meters

To achieve accurate flow measurements, ensure the upstream and downstream piping of flow meters is properly designed. Follow manufacturers' recommendations carefully.

3.3 *Head flow meters* Head flow meters measure the change in pressure that occurs when a fluid is forced through a restriction in the flow path, according to the general equation:

$$Q_v = KA\sqrt{\frac{2\Delta p}{\rho}}$$

where Q_v = volume flow rate (m^3/s)
A = cross-sectional area of the stream through the restriction (m^2)
K = calibration constant specific to the flow meter
Δp = pressure differential across the restriction (Pa)
ρ = density of the fluid (kg/m^3)

A differential pressure transmitter converts the differential pressure across the meter to an electronic signal. The signal is generally nonlinear, so use a root extractor to derive a linear signal, if required.

The turndown of a typical head flow meter is 3:1. For example, a meter designed for a flow rate of 30 L/s can reliably measure a minimum flow of 10 L/s. Expect accuracies from 1.5 to 2% of full scale.

Some of the more common head flow meters are Venturi tubes, Dall tubes, orifice plates, flow nozzles, and Pitot tubes. Use these meters with clean liquids and gasses.

3.4 *Electromagnetic flow meters* Electromagnetic flow meters measure the volume flow of electrically conductive liquids passing through a magnetic field in a pipe tube. Because of their relatively high cost, use these flow meters only when wide range and high accuracy are required or when metering corrosive, dirty, or viscous liquids.

Typical turn down for an electromagnetic flow meter is 20:1 with an accuracy of 1% of full scale. The output signal is linear with the measured flow rate.

3.5 *Velocity flow meters* Velocity flow meters usually use a turbine or propeller to sense the flow of a moving fluid. A series of pulses makes up the output signal from velocity meters. The pulse rate increases with flow rate. A frequency-to-current transducer in the meter generates an analog signal by converting the pulses to 4–20 mA current. The analog signal is linear with flow.

Both turbine and propeller meters have turndown ratios of 15:1. Turbine meters achieve accuracies of 0.5% of full scale. The accuracy of propeller meters rests at 1% of full scale.

Do not use turbine meters in liquids containing solids or where there is a possibility of entrained air entering the liquid stream.

3.6 *Volumetric flow meters* Volumetric, or positive displacement, flow meters divide the flow stream into parts and count them as an indication of total flow. Some common volumetric flow meters are:

- nutating disk
- gear or lobed impeller
- sliding vane
- rotating vane
- reciprocating piston
- oscillating piston
- diaphragm

Similar to velocity flow meters, volumetric meters generate output signals as a series of pulses. A frequency-to-current transducer converts the pulses to current analog signals of 4–20 mA that are linear with flow.

Volumetric flow meters typically achieve turndown ratios of 10:1 and accuracies of 1% of full scale.

Use these meters for clean fluids only.

3.7 *Ultrasonic flow meters* Ultrasonic flow meters respond to the propagation of pulsed signals into a flowing liquid. The meter derives the flow rate from the time difference that occurs in upstream and downstream frequencies. Ultrasonic meters produce output signals linear with flow.

The turndown of ultrasonic meters is 20:1 and they achieve accuracies of 1% of full scale.

Ultrasonic meters suit a wide variety of applications, including dirty, corrosive, and viscous liquids, and large pipe flow measurement. Some ultrasonic meters can be readily added to existing piping systems. However, users report mixed results with this type of meter. Take care in selecting and using ultrasonic flow meters.

3.8 *Vortex-shedding flow meters* Vortex-shedding flow meters respond to velocity flow by employing the vortex precession principle. A swirl component causes the flow to produce a high-velocity, twisting vortex. When the vortex enters an enlarged area it forms a helical path around the meter body. Measuring the frequency of the helical precession determines flow.

The turndown for vortex meters can reach 100:1 and they achieve accuracies of 1% of full scale. The output signal is linear with flow.

Use vortex-shedding flow meters with clean fluids.

3.9 *Force-displacement flow meters* Force-displacement flow meters respond to the force exerted by a flowing fluid on an obstruction

inserted into the fluid. The force causes the primary element to deflect. The deflection varies with the differential pressure and indicates the flow rate.

These meters have a typical turndown of 5:1 and an accuracy ranging from 1 to 5% of full scale. Use force-displacement meters to measure the flow rate of both fluids and solids.

3.10 *Mass flow meters* Choose from two types of mass-flow measurement devices for granular materials:

- weigh belt
- weigh dump hopper

Typically, the weigh belt consists of a short conveyor mounted on strain gage load cells. The mass flow meter measures belt speed and belt weight and calculates instantaneous mass flow. Some weigh belt equipment produces a 4–20 mA output signal, which is linear with flow rate. This type of flow meter can achieve accuracies of 1%.

The weigh dump hopper operates by repeatedly filling a container, weighing its contents, and emptying the container. The total of the number of batches and their weights serves as a measurement of the flow rate. Weigh dump hoppers allow high-volume measurement with accuracies of 0.1%.

3.11 Pressure transmitters

The most common types of pressure transmitters are gage and differential. These transmitters determine pressure by measuring the deflection of a diaphragm, bellows, or Bourdon tube. A variety of devices sense the deflection, including strain gages, variable capacitance and reluctance meters, piezoelectric gages, differential transformers, and potentiometric devices.

Industrial instrumentation generally relies on strain gages to measure deflection. Commercial applications more commonly use potentiometric devices. In all cases, electronic circuitry converts the signal from the primary element to 4–20 mA. Often the transmitter integrates the conversion circuitry so only two conductors are required.

Pressure transmitters primarily measure levels. However, when used with a head type primary element, they also measure flow. In both cases, choose a differential transmitter. Differential pressure transmitters can also be used to measure vacuum.

When using a Bourdon tube on pulsating pressures or in areas of high vibration, add oil damping to reduce possible damage to the Bourdon element.

3.12 Temperature sensors

Temperature sensors vary according to the fundamental operating principles of the sensing elements. Select the transmitter according to operating temperature range, cost, and the number of points to be measured. Among the most common temperature sensors are:

- thermoelectric sensors
- thermoresistive sensors
- filled-system sensors
- integrated-circuit sensors

3.13 *Thermoelectric sensors* Thermoelectric sensors, or thermocouples, consist of a pair of wires of different metals joined at the end. If two junctions are at different temperatures, a voltage develops. One junction, the reference junction, is kept at a constant, known temperature so the voltage produced is directly proportional to the temperature at the second junction, the measuring junction. Thermocouple wire combinations vary, depending on their application.

However, the very small voltage that thermocouples produce limits their operation. Stray currents in the circuit dramatically alter the measured current value. To correct this situation, use special wiring and terminals made of the same basic material as the thermocouple to connect the sensor with the output equipment.

In general, thermocouples cost less and suit more situations than most other temperature measurement devices. Select the correct thermocouple material for a given temperature range to ensure the thermocouple output signal is linear with temperature. The comprehensive catalogs generally available from suppliers aid in thermocouple selection.

3.14 *Thermoresistive sensors* Thermoresistive sensors, or resistance temperature detectors (RTDs), operate on the principle that the resistance of a metal wire changes with temperature. Although all metals possess this characteristic, only copper, nickel, and platinum exhibit acceptable resistance to be used in the construction of RTDs.

Different from thermocouples, RTDs retain their accuracy regardless of the distance between the point of measurement and the point of connection to the output equipment. Also, variations of temperature along this distance have little effect on the accuracy of the RTDs, especially when they consist of four wires.

3.15 *Filled-system sensors* The thermal expansion of a fluid in a sealed system actuates some temperature transmitters. A strain gage or potentiometer measures deflection of a diaphragm or piston, operating in much the same way as in pressure transmitters.

Often integral electronics that have an output signal of 4–20 mA accompany filled system sensors. This output signal is linear with temperature.

Use filled-system sensors to determine the average temperature in a space. These systems accomplish the temperature measurement via capillary tubing designed to be sensitive to temperature over a long length.

Thermal expansion temperature transmitters are relatively expensive. However, their simple installation requirements offset the high cost, especially in control systems requiring only a few temperature measurements.

3.16 *Integrated-circuit sensors* Integrated-circuit sensors are a relatively new sort of temperature measurement instrumentation. They offer low cost and linear, stable output signals for temperatures ranging from $-100°C$ to $+150°C$.

3.17 Power measurement

Information from power measurement provides a variety of data concerning the operation of control systems. Used directly, power measurements allow the control system to protect motors or limit peak demand charges from an electric utility company. Indirect power measurements can serve as indicators of mechanical equipment operation. In systems with large motors, power measurements in conjunction with programmable controllers reduce power factor problems and utility company charges.

Two primary elements operate in power measurement:

- current transformer (CT)
- potential transformer (PT), or potentiometer

CTs are doughnut-shaped devices. The wires powering a load pass through the centre of the CT. CTs generate an output signal, usually 0–5 A, over the normal operating current of the load.

PTs connect across power lines and generate output signals proportional to input voltage.

Several different devices accept the CT and PT signals and provide signals of 4–20 mA representative of such things as motor current, power factor, phase imbalance, and kilowatts. The signal of 4–20 mA serves as an input to conventional analog switches or to programmable controllers. These signals also operate meters.

3.18 Rotation sensors

Two devices commonly measure the rotational speed of a shaft:

- tachometer generator
- optical or magnetic sensor

The tachometer generator produces an alternating current of a frequency proportional to the rotational speed. The optical and magnetic sensors produce a series of pulses at a frequency related to shaft speed.

In most cases current transducers convert the signals from the speed sensors to signals of 4–20 mA. Some programmable controllers, though, allow direct input of frequency signals.

3.19 Position sensors

Gear-driven potentiometers or optical shaft encoders generally determine the position of such equipment as gates, valves, or distributors.

Potentiometric sensing offers the simplest and least expensive alternatives. However, potentiometers require resistance-to-current transducers to convert position signals into current signals of 4–20 mA.

Optical shaft encoders are more accurate than potentiometers but cost much more. Optical encoders generate analog signals of 4–20 mA or several types of digital signals. The digital output signals can directly connect to some programmable controllers, but wiring from the sensor to the controller may require signal amplifiers over long distances.

3.20 Relative humidity sensors

Most relative humidity (RH) sensors are designed for commercial heating and ventilation applications and therefore do not suit severe environments. A few types of RH transmitters, in which the electronics mount in settings remote from the primary sensing device, may function in some demanding environments. Nonetheless, because reliable RH sensors are difficult to find, be careful when designing control systems based on humidity measurement.

4 PHASE CONVERTERS

Most farming applications rely on single-phase electric motors because of the availability of only single-phase power service in rural areas. However, a growing demand for larger motors on farms has created a need for three-phase motors. These motors offer several advantages over their single-phase counterparts.

Three-phase motors, especially those larger than 1.5 kW, provide a wide choice of operational characteristics and are less expensive than single-phase motors of the same horsepower rating. As well, three-phase motors do not require starting windings and starting devices, which reduces problems in servicing and maintenance. Also, three-phase motors are usually smaller, lighter, and simpler in construction.

To incorporate three-phase motors into rural applications previously served by single-phase motors, use a phase converter, particularly in these situations:

- when the cost of bringing three-phase power to the location is high because of the construction costs for the required length of three-phase extension
- when the rate structure for three-phase service is higher than that for single-phase service
- when a load requires the power of a large motor but starting currents exceed those allowed by the power supplier for across-the-line starting
- when temporary three-phase service serves until regular three-phase service becomes available
- when a three-phase motor is an integral part of certain equipment and replacement of the motor is either difficult or expensive.

5 VARIABLE-SPEED DRIVES

Until recently, the most common variable-speed drive used a special motor winding and varied the field current using conductive liquid and electrodes. Developments in high-voltage and solid-state current devices, however, have led to variable-speed drives that operate with standard induction motors. These solid-state drives, as powerful as 40 kW, are efficient and reliable for materials-handling applications. Use variable-speed drives, for example, on loads such as conveyors, pumps, and blowers.

Because the power input can be set to match the load requirements, variable-speed drives are more efficient than fixed-speed motor control systems. Variable-speed drives also limit the inrush current to the motor, so a larger motor can be used in rural applications.

Some solid-state speed controllers allow single-phase electrical service to connect through the variable-speed controller to a three-phase motor. This feature helps control air blower pressure in drying grain, especially when only single-phase electrical service is available. With a solid-state controller, the motor current, and correspondingly the blower output, matches both the requirements of the process and the inherently soft-start characteristics of the variable-speed drive. Coupling this setup with the ability of some variable-speed drive systems to connect a single-phase source to a three-phase motor allows a much less expensive solution to grain drying than traditional approaches, such as multiple small motors and blowers.

When using variable-speed controllers, however, be wary of the undesirable harmonic frequencies some variable drives produce on the power supply. Electrical supply authorities strictly limit this type of interference. Therefore, before selecting a variable-speed drive, determine its expected harmonic effects on the electrical grid.

6 MOTOR CONTROL

Starters control motors by applying or interrupting power. Motor starters are available in a wide variety of enclosures and voltage ratings and for motor sizes up to thousands of kilowatts. Select a starter based on the environment in which it is intended to operate, the type of motor connected to it, and whether it requires remote or automatic control.

The *Canadian Electrical Code* requires that all motor circuits be electrically protected. Fuses or circuit breakers protect motors against short circuits. Overloads prevent motors from overheating. The code also specifies the sizes of circuit breakers and overloads in motor starters.

For larger facilities using several motors, a motor control centre can be economical. This centre mechanically groups the combination motor starters near a common power bus and simply locates starter switches near the motors or in the facility control centre. Motor control centres are available in several enclosure types, including explosion-proof containers; but most systems are designed with the motor

control centre located in a general-purpose area. In dusty environments that contain no explosives, specify EEMAC 12 enclosures, so designated by the Electrical and Electronic Manufacturers Association of Canada.

Where the motor circuit breaker is integral with the motor starter, the unit is called a combination starter.

6.1 Overloads

Two kinds of devices provide motor overload protection:

- electronic devices that measure motor current with current transformers
- overload relays that carry the motor current through heater elements

Electronic motor overload protection provides sophisticated monitoring of motor conditions. As well as measuring motor current, these devices can monitor actual motor conditions, such as winding temperature and bearing temperature. Then, based on these measurements, the protective devices shut down the motor or prevent frequent starts.

In the case of overload relays, the motor current heats a heater element. When the temperature reaches a preset limit, the motor automatically disconnects from its power supply. Industry standards designate an overload relay by a class number that indicates the maximum time, in seconds, at which the relay trips when carrying a current equal to 600% of its current rating. These classes are class 10, class 20, and class 30. Choose class 20 for general applications.

Select overload heaters according to application. Manufacturers' tables help in matching the overload heater with motor starter size and motor running current. However, if the motor starter resides in an environment in which ambient temperatures are different from the motor, be careful to adjust the overload heater size to compensate for the difference.

6.2 Manual starters

A manual motor starter automatically stops the motor when an overload occurs. All other motor control must be done manually.

6.3 Magnetic starters

Magnetic starters allow motors to operate remotely from several locations. The control can be either manual or automatic, or a combination.

A starter generally consists of simple electrical contacts that carry current to the motor. Additional auxiliary contacts (either normally open or normally closed) fitted on the starter allow it to interconnect with other control circuits and provide interlocking between motors or to monitor motor status remotely. These same contacts can also operate such equipment as valves or gates.

6.4 Reversing starters

Reversing starters, either manual or magnetic, usually operate with three-phase motors. The reversing of a three-phase motor requires only that two of the three leads powering the motor be interchanged.

Reversing starters consist of six contacts carrying high current: three contacts close for forward operation and three others close for reverse. A mechanical interlock on manual reversing starters ensures that both sets of contacts cannot close at one time.

Magnetic reversing starters use two coils and at least two normally closed auxiliary contacts, one operating from each coil, along with the basic configuration of six high-current contacts. These auxiliary contacts connect in series with the opposite coil to prevent both coils from energizing simultaneously. As well, magnetic reversing starters have both mechanical and electrical interlocks.

6.5 Reduced-voltage starters

The starting current of an electric motor can reach six times the normal running current. This situation may place an unacceptable demand on the power supply, especially with large motors. Reduced-voltage starters start the motor at a slow speed then gradually power it to full speed. This situation limits the starting torque of the motor.

The use of reduced-voltage starters depends on three factors:

- voltage—higher voltage motors require less current for the same power
- size of the electrical service
- requirements of the electrical supply utility

There are two types of reduced-voltage starting configurations: open- and closed-transition. With open-transition reduced-voltage starters there is a momentary break in the current flow at the change from start to run. Switching is simpler as a result.

However, the momentary break in motor current that occurs with open-transition circuits can cause a transient, high-current spike.

These transients can disrupt an electrical distribution system or cause malfunctions in sensitive devices such as computers and other electronic control devices. Take care when selecting open-transition reduced-voltage starting equipment.

Closed-transition starters, on the other hand, do not allow a break in current flow. The motor starter contacts are arranged so the step from start to run overlaps.

These are the most common reduced-voltage starters:

- Wye-Delta starters
- autotransformer starters
- primary-resistor starters
- part-winding starters
- solid-state starters
- variable-speed starters

6.6 *Wye-Delta starters* Wye-Delta starters require specially wound motors. Use them in configurations where low starting torque is acceptable, for example for high-inertia loads or when a long acceleration time is required.

6.7 *Autotransformer starters* Use autotransformer starters with any standard squirrel cage motor, adjusting the inrush current by changing taps on the transformer. Remember, the lower the inrush current, the lower the starting torque. Autotransformer starters provide the highest starting torque per line ampere.

6.8 *Primary-resistor starters* These starters operate similar to autotransformer starters but use resistors instead of transformer windings to limit the inrush current.

6.9 *Part-winding starters* Use this type of starter with a part-winding motor to reduce inrush current to about 60% of normal. These starters also suit applications in low-starting torque motors.

6.10 *Solid-state starters* For standard, three-phase, squirrel-cage motors use solid-state starters that operate with reduced voltage. These starters employ a series of power semiconductors that hold circuit power constant until the motor reaches full speed. Operators can adjust starting currents from 30 to 80% of normal inrush.

6.11 *Variable-speed starters* Variable-speed drives also function as reduced-voltage starters, although the drives are more complex and more expensive than standard starters. Use variable-speed starters in applications requiring both variable-speed and reduced-voltage starting.

7 TYPICAL CONTROL CIRCUITS

The information in this chapter demonstrates how to interconnect various components to provide control functions. The six typical control circuits include:

- stop/start motor controls
- timing circuits
- alternator circuits
- stepping circuits
- signal-conditioning circuits
- analog switch circuits

7.1 Stop/start motor controls

Almost all control systems use stop/start motor controls (Fig. 1), the simplest of relay circuits.

The start button, a normally open momentary switch, passes power when it is pressed. The stop button, a normally closed momentary switch, passes power continuously until it is pressed.

As the operator presses the start button, power passes through both the start and stop buttons to energize the relay coil. Then a contact in the relay closes, also passing power to the stop button. Thus if the start button is released, the contact in the relay coil still supplies power. In fact, the relay remains energized until the stop button is pressed to interrupt power. Releasing the stop button, however, does not re-energize the relay because the relay contact remains open, breaking this section of the power circuit.

The contact in this type of circuit is often called a holding, or sealing, contact and the circuit, a holding circuit. If a power failure occurs, the circuit de-energizes and does not re-energize until the start button is pressed.

Other devices besides motors also rely on start/stop circuits, for example differential level controls. In level controls, level switches replace the start and stop buttons; one level switch acts as a start, the other acts as a stop.

7.2 Timing circuits

Two common timing circuits are:

- on-delay circuits
- off-delay circuits

7.3 *On-delay circuits* An on-delay circuit allows one device to energize (or de-energize) a set time after another device energizes. For example an on-delay circuit postpones the closing of a pump bypass valve until after the pump has started (Fig. 2).

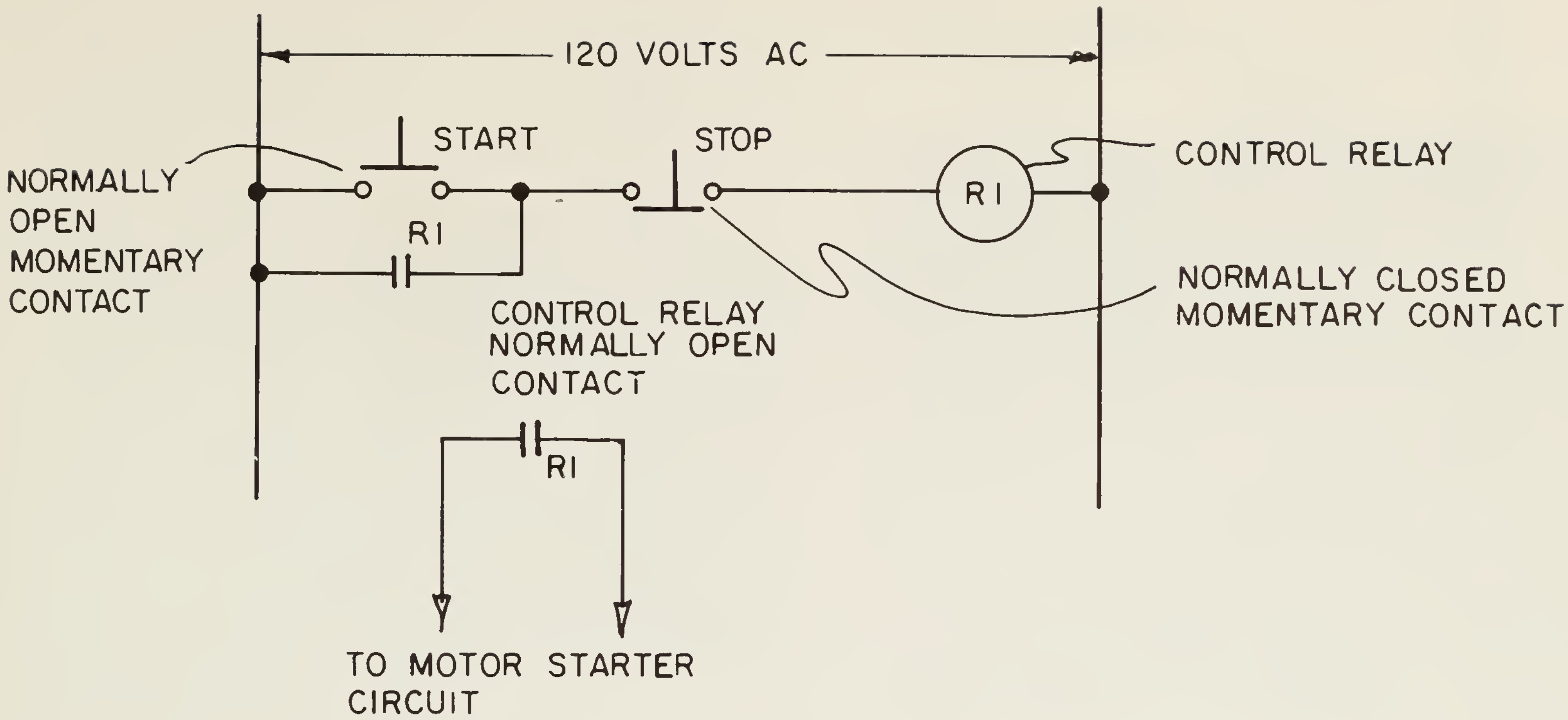

Fig. 1. Stop/start motor control.

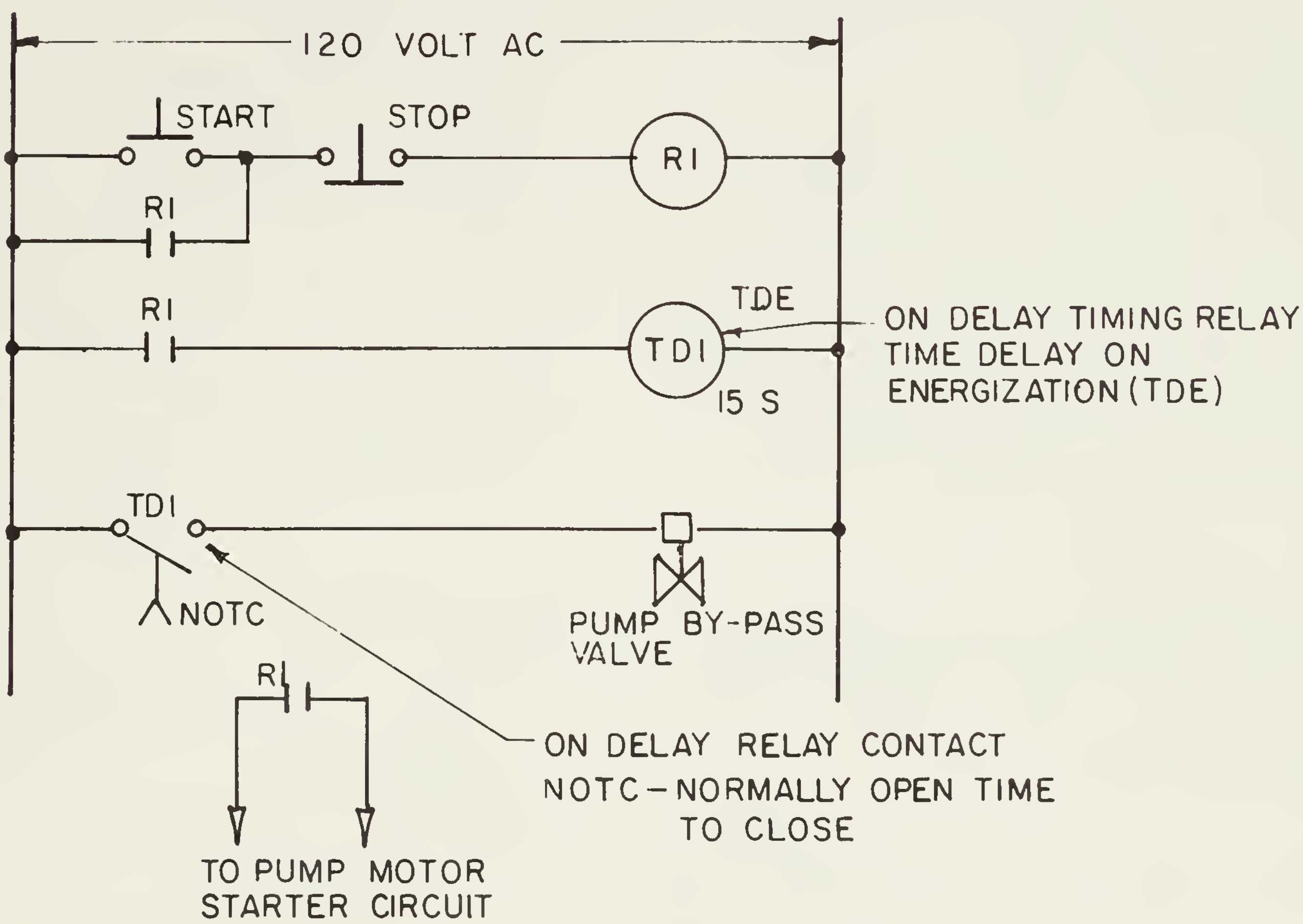

Fig. 2. Pump bypass circuit.

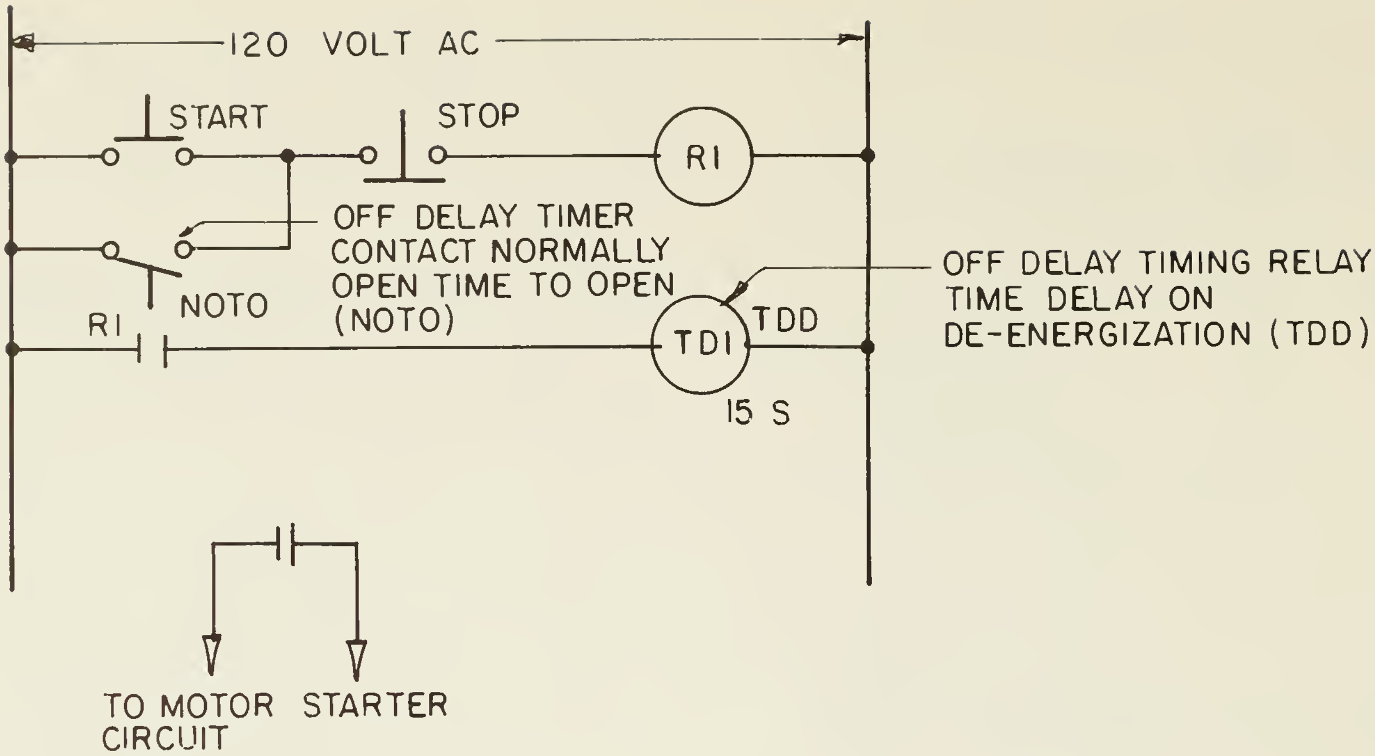

Fig. 3. Restart circuit.

7.4 *Off-delay circuits* Use off-delay circuits when one device must energize (or de-energize) a set time after another device (or circuit) de-energizes. A motor restart circuit, for example, uses this kind of circuit. An electropneumatic, off-delay timer connected in a motor circuit allows a start/stop circuit to remain active for a certain time period after a power failure. In this circuit the start button energizes a timing relay with a holding contact around the start button. Should power fail, the contact remains closed until the timer reaches the specified time out. If power is restored within the time-out period, the circuit re-energizes (Fig. 3).

7.5 Alternator circuits

In some applications two motors share the load by alternating their operation. Consider a two-motor air compressor system (Fig. 4). Each time the pressure switch calls for a motor to start, the circuit selects the motor that did not operate in the previous cycle.

Electromechanical relays commonly perform this logic using a special pair of contacts. The pair of contacts consists of one contact normally open and one normally closed. They are arranged so that when the relay energizes or de-energizes, one contact closes before the other opens. In Fig. 4, relay R1 operates motor 1 and relay R2 operates motor 2. Relay R3 retains the information on whether motor No. 1 was the last to operate. When the pressure switch first energizes the circuit, both R3 and R2 are de-energized and power flows to the coil of R1. R2 cannot energize initially because R3 is not yet energized, so the R3 contact in that circuit cannot pass power. When R1 energizes,

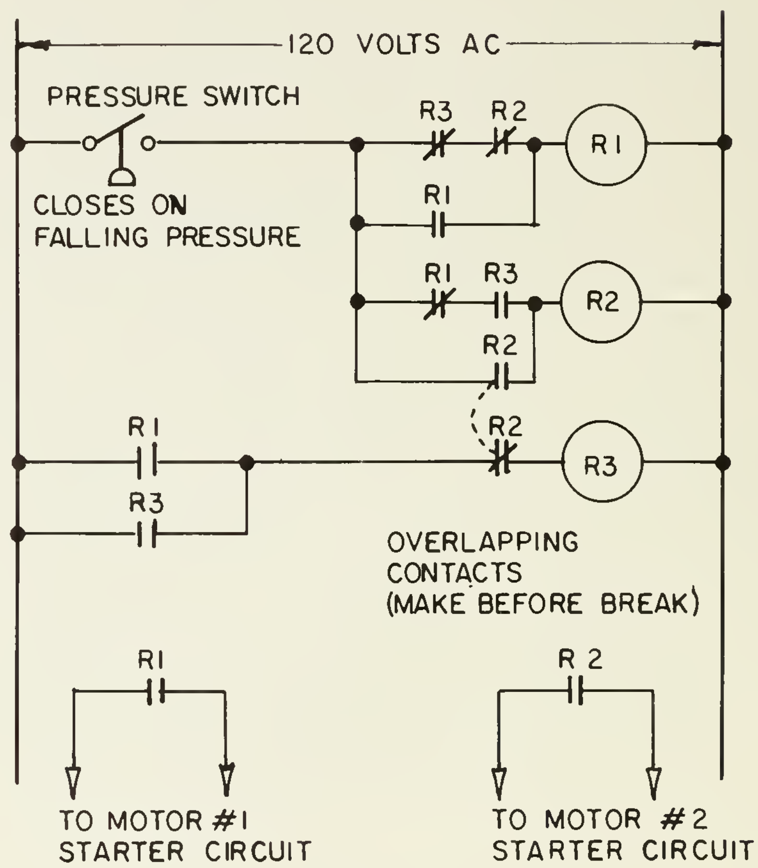

Fig. 4. Alternator circuit.

R3 also energizes and seals itself with its holding contact. Finally, when the pressure switch opens, indicating that the air tank pressure is now high enough, R1 de-energizes but R3 remains energized through its holding contact.

When power next enters the relay circuits, the R3 holding coil prevents R1 from energizing. Instead, R2 energizes. R2 seals its own circuit with the R2 contact in parallel with R3 and R1 contacts. When R2 energizes, R3 de-energizes because R2, a normally closed contact, opens. The overlapping R2 contact gives the R2 coil a chance to seal itself before the R3 contact opens. Without this overlapping, R2 and R3 would attempt to open simultaneously with unpredictable results. Programmable logic controllers help to avoid any unpredictability because of the way in which they solve the logic (see section 2.23).

7.6 Stepping circuits

A stepping circuit relay consists of two or more normally open contact sets. These contact sets close individually each time the relay coil energizes and de-energizes.

A stepping circuit can be used in place of the alternator circuit in the air compressor system described in section 7.5. If a two-step stepping relay were used in that system, the coil of the stepping relay would connect directly to the pressure switch. The two output contacts from the relay would also connect to the switch. Thus, each contact would connect to the two circuits in the air compressor motor. Every time the pressure switch operates, the stepping relay would open one set of output contacts and close another.

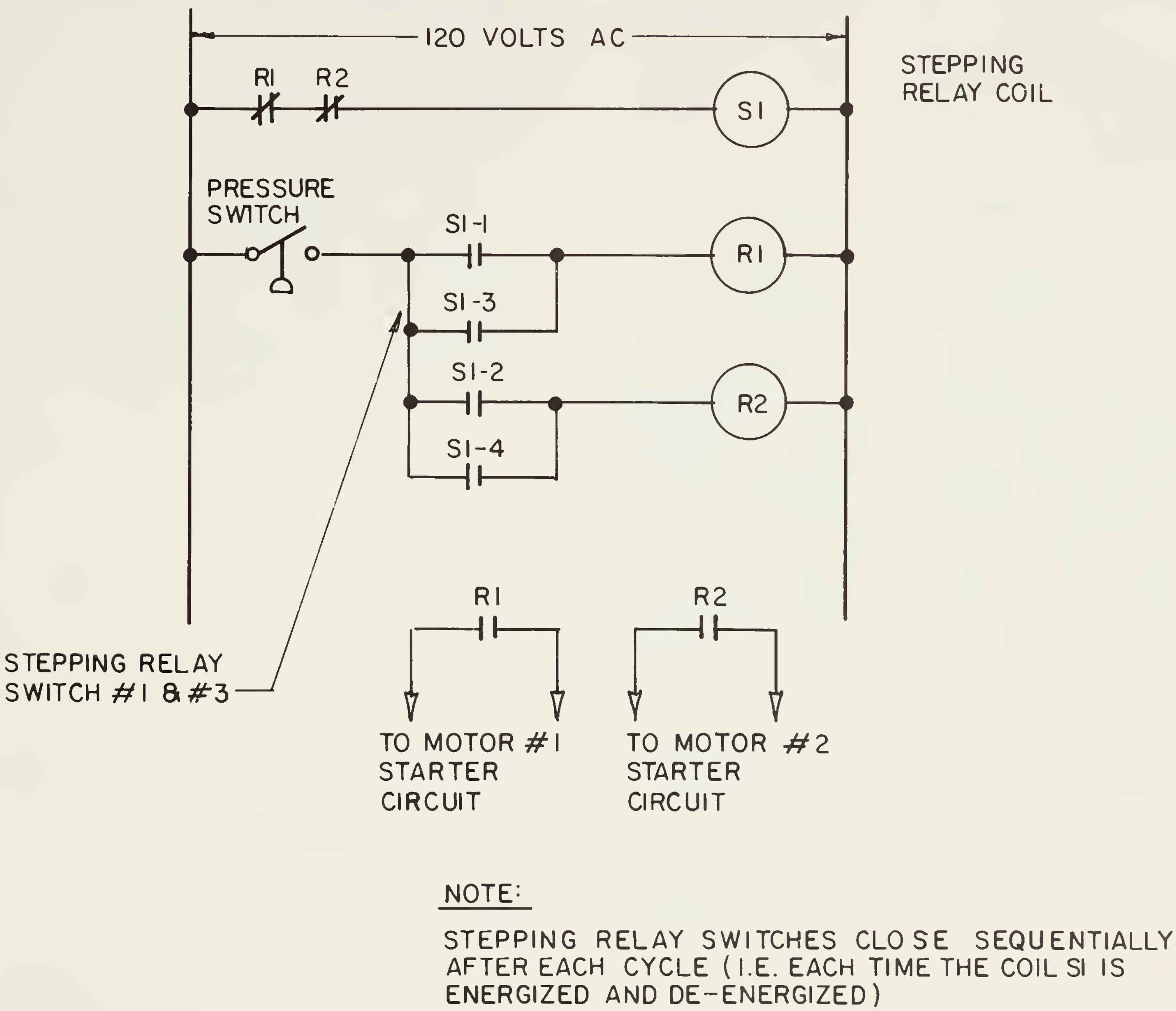

Fig. 5. Stepping switch circuit.

Alternatively, multiple-step stepping switches could connect every other output contact to each motor circuit. Fig. 5 illustrates a four-step switch used for alternating two motors.

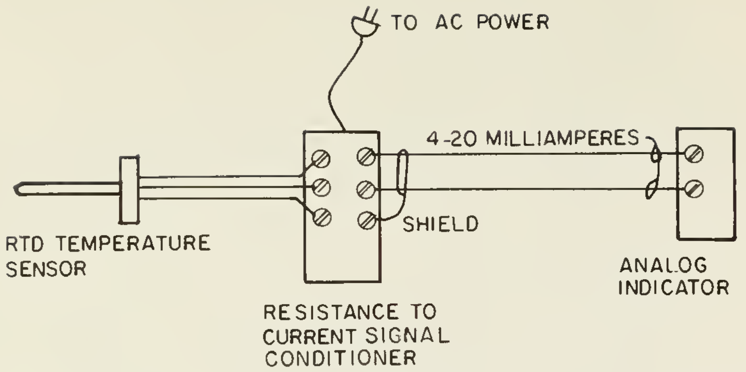

Fig. 6. Signal-conditioning (RTD) circuit.

7.7 Signal-conditioning circuits

The signals from analog sensors often require modification or amplification before a control circuit can use them. Fig. 6, for example, illustrates a resistance temperature detector (RTD) connected to a resistance-to-current signal conditioner. The output of the signal conditioner, a signal of 4–20 mA, connects to an indicator. On the scale, 4 mA represents 0°C and 20 mA represents 100°C. Adjusting two potentiometers (called zero and span) in the signal conditioner sets the measurement scale for the RTD sensor signal.

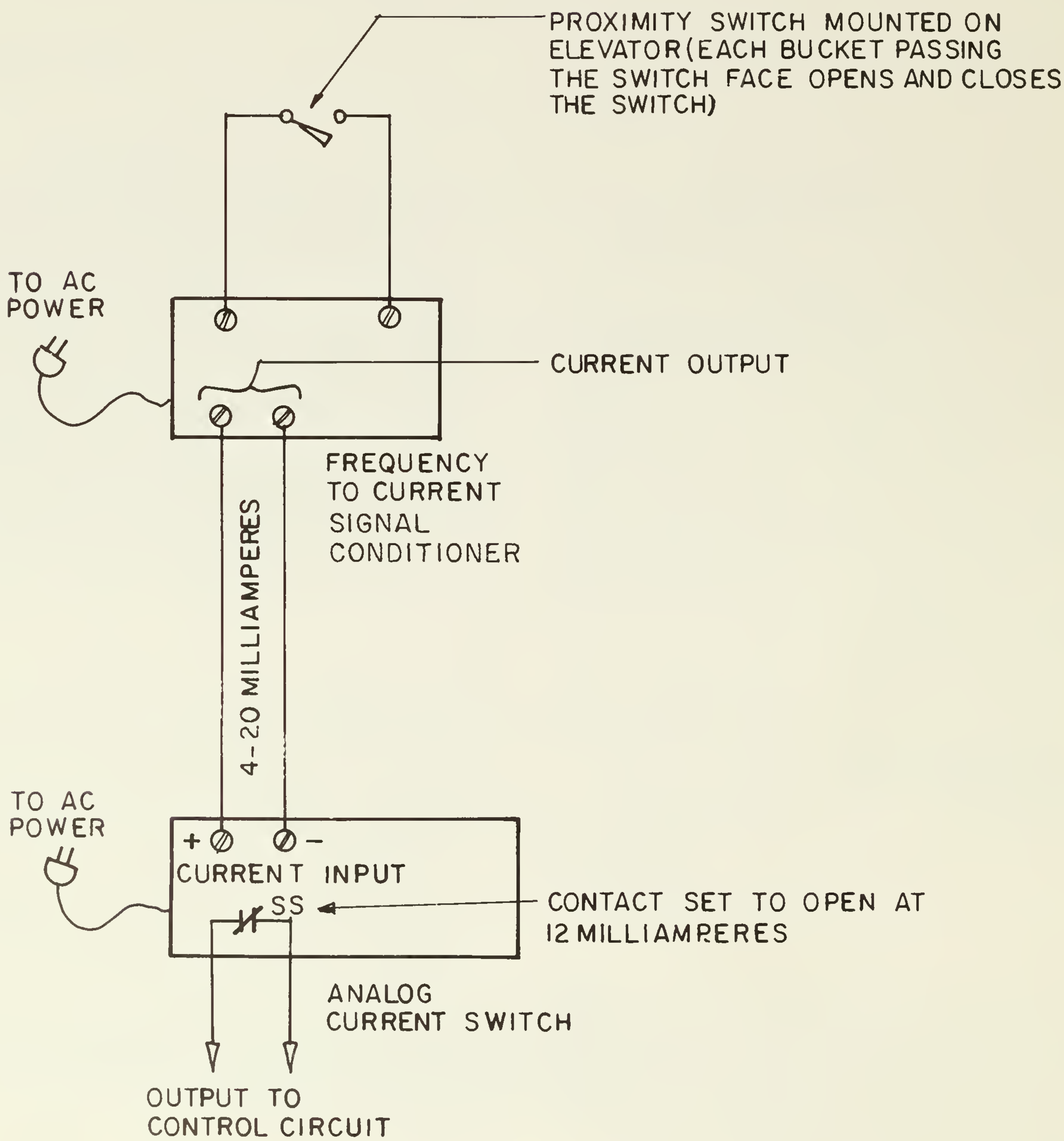

Fig. 7. Analog signal wiring detail.

Other measurements that may require similar signal conditioning include:

- motor current, where a current-to-current transducer connects to a current transformer in a motor circuit
- shaft speed, where a frequency-to-current transducer connects to a shaft rotation switch
- weight, where a strain gage connects to a millivolt-to-current transducer

7.8 Analog switch circuits

Proximity switches, connected to signal conditioners, can open or close output contacts based on predetermined milliampere signals (Fig. 7). Use these analog switches to control circuits with temperature switches, speed switches, overcurrent switches, or weight switches.

Fig. 8 shows an analog speed switch in a bucket elevator circuit. The switch stops the elevator motor if the elevator speed falls below a preset value. In this example, relay R1 energizes when the operator presses the start button. Timing relay TD1 energizes when R1 energizes and begins timing. If the speed signal from the frequency-to-current signal conditioner produces an output of at least 12 mA, the analog switch opens its output contact and de-energizes TD1. This action prevents TD1 from operating its contact in the R1 relay coil circuit. However, if the analog switch contact fails to open within 5 s after the motor starts, TD1 opens the circuit to R1, thus stopping the motor until the start button is pressed again.

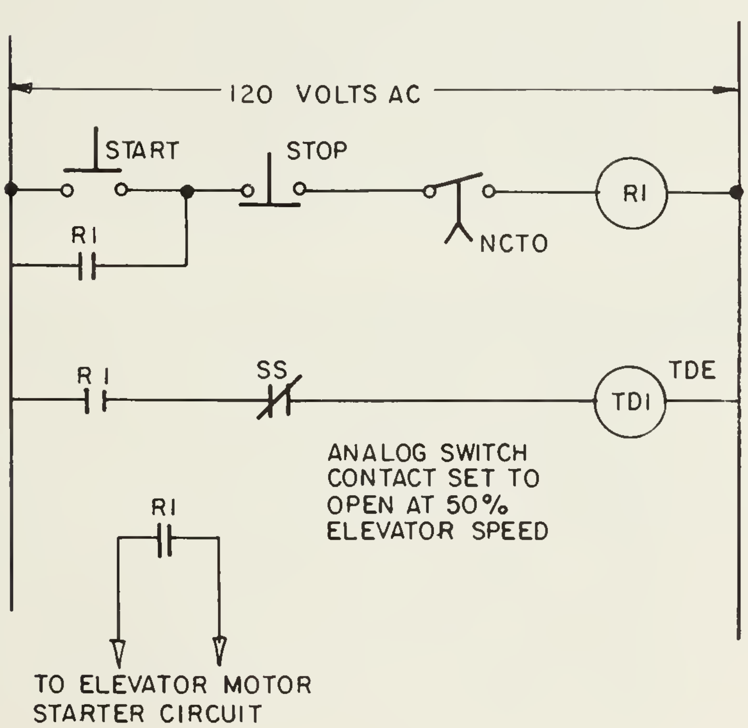

Fig. 8. Bucket elevator control circuit.

8 CIRCUIT DIAGRAMS

Designing control systems involves several kinds of diagrams. Here are the four most common types:

- logic flow diagrams
- ladder diagrams
- wiring diagrams
- loop diagrams

8.1 Logic flow diagrams

Producing a logic flow diagram represents the first step in the development of a control system. Flow diagrams, also called flow charts, identify all the steps used in sequential control. These diagrams serve several important purposes for control system designers:

- to itemize the hardware requirements
- to identify the number of inputs and outputs
- to characterize the timing elements needed
- to specify the interrelationships between the various input and output signals

In addition, individuals not familiar with electrical and electronic equipment or schematic diagrams can use flow charts to review the intent of the control system design.

The complexity of flow diagrams ranges from very basic system overview to detailed description of each of the elements in the control system. The level of detail depends on the complexity of the control system, the number of interrelated control sequences, and the need to convey the intent of the design to individuals not familiar with electrical system design. The experience of the system designer also influences the form of the flow diagrams. For experienced designers, often only the most complex systems require flow diagrams.

Fig. 9 illustrates the mechanical arrangement of a simple system for a conveyor. The control system must monitor the target bin level and stop the conveyor as the grain reaches a preset high level. The design of the conveyor specifies that if the gate to bin 1 is not open, the conveyor must automatically direct the grain to bin 2. Should the conveyor shaft stop turning, the conveyor motor must stop.

The flow chart for this system (Fig. 10) identifies the logic functions required to satisfy the design criteria.

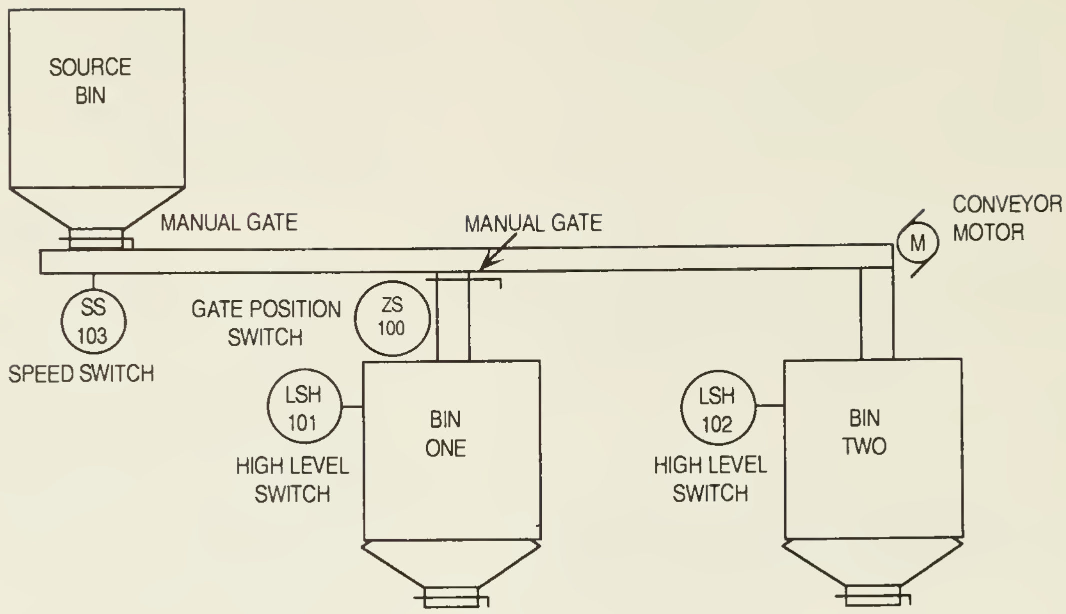

Fig. 9. Conveyor system mechanical arrangement.

8.2 Ladder diagrams

Ladder diagrams present schematic wiring illustrations for individual components in a control system as well as all the interconnections between them. Designers develop these diagrams after selecting all the system hardware. Ladder diagrams do not show the physical layout of the components or their relative sizes.

There are several conventions used to identify relay coils, contacts, timing and stepping relays, and termination points on ladder diagrams. Fig. 11 shows the chart of symbols most commonly used. Typically, solid lines indicate wiring inside control panels, and dotted lines indicate external wiring.

Fig. 12 illustrates the ladder diagram for the conveyor control system shown in Fig. 9. The ladder diagram is arranged with the various components making up the rungs of the ladder and the power lines, hot and neutral, making up the vertical members of the ladder. Each of the rungs receives a line number. This number serves several purposes:

- to cross reference relay contacts
- to identify the relay and timer coils
- to identify terminal blocks

For example in Fig. 12, R101 identifies a relay coil on line 101 of the ladder diagram. The location of each of the relay contacts is identified to the right of the relay coil. Simple line numbers designate normally open contacts; underlined numbers indicate normally closed contacts. Terminal blocks are similarly numbered. The line number forms the prefix to the number of the terminal block. Thus the first terminal block on line 102 is numbered 1021, the second 1022, and so on. The lamp symbol indicates a lamp with the lamp color shown inside the symbol (e.g. R = red).

For the conveyor system (Fig. 12), a momentary start button on line 105 starts the conveyor. If the gate to bin 1 is fully open, relay 101 energizes and the contact R101 in line 105 closes. Power passes from the start button through the normally closed stop button to the normally closed contact R102. Contact R102 on line 105 closes only if the high-level switch LSH101 on line 102 is not closed, and thus when relay R102 is not energized. If the gate to bin 1 is not open, the normally closed contact R101 on line 106 allows power to pass

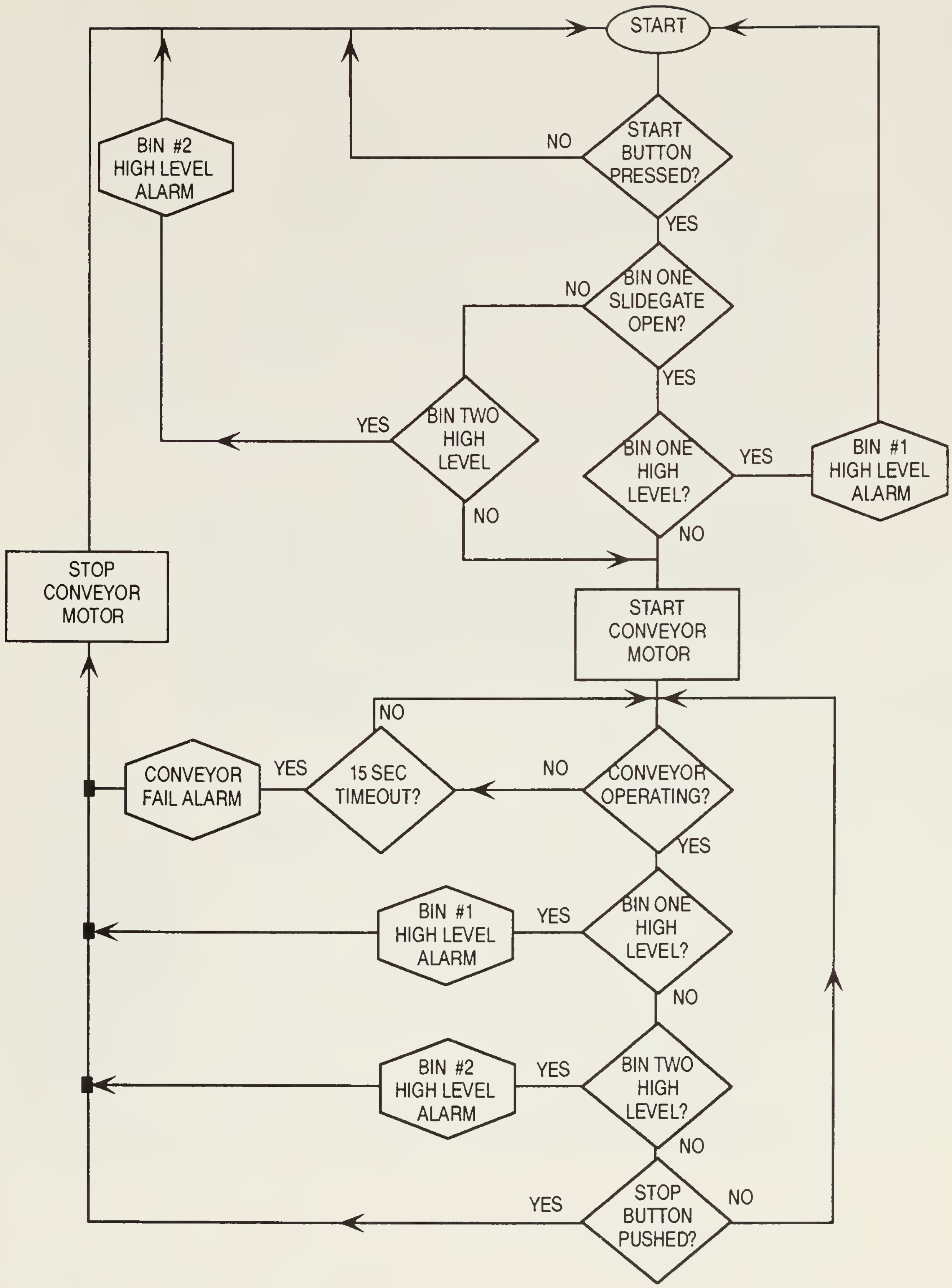

Fig. 10. Flow chart for bin transfer system.

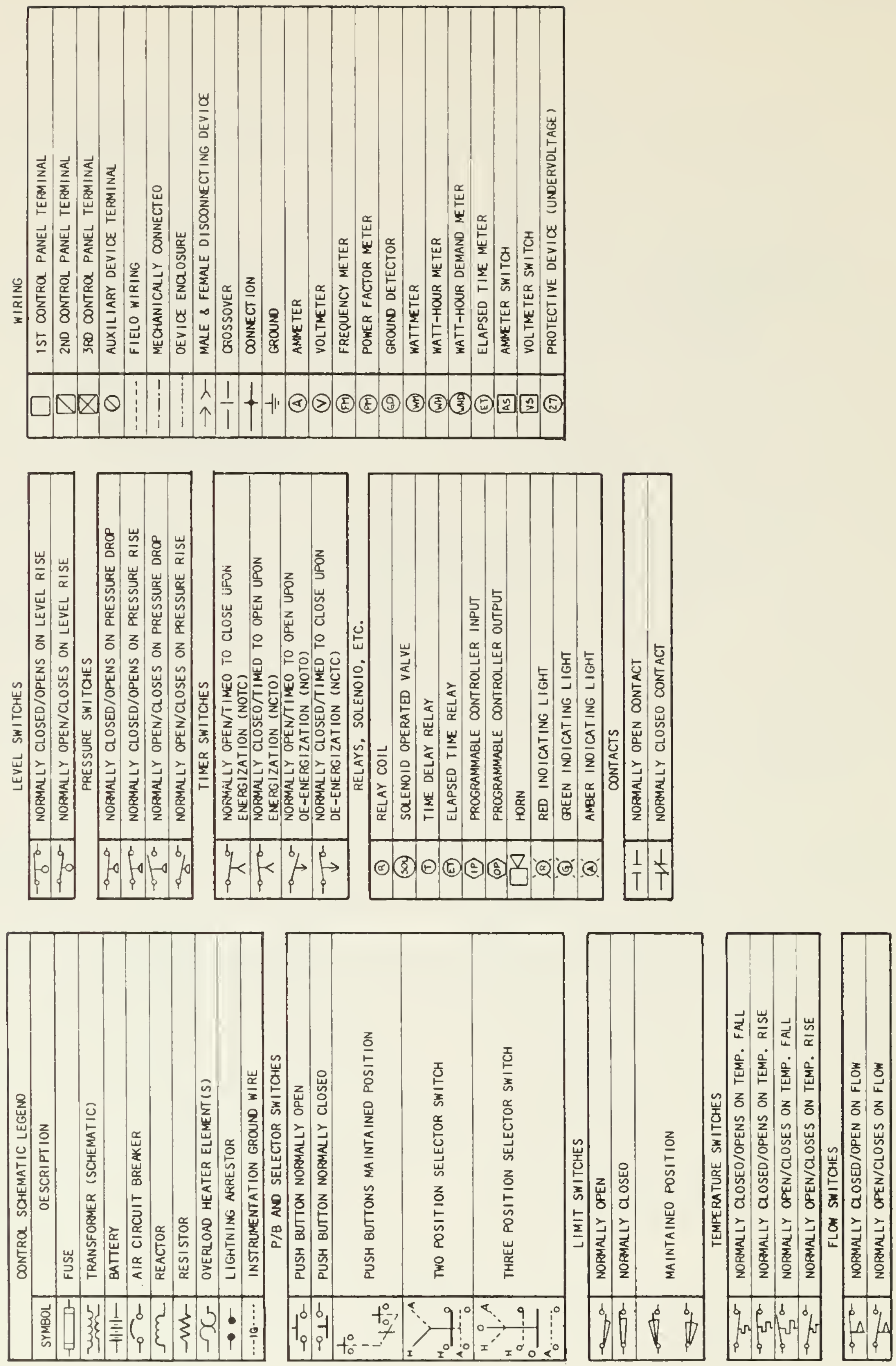

Fig. 11. Symbols for ladder diagrams.

to the bin 2 high-level relay contact R103 on line 106. So, either if the gate to bin 1 is open and there is no high level in that bin or if the gate to bin 1 is not open and there is no high level in bin 2, then timer contact T108 on line 105 receives power.

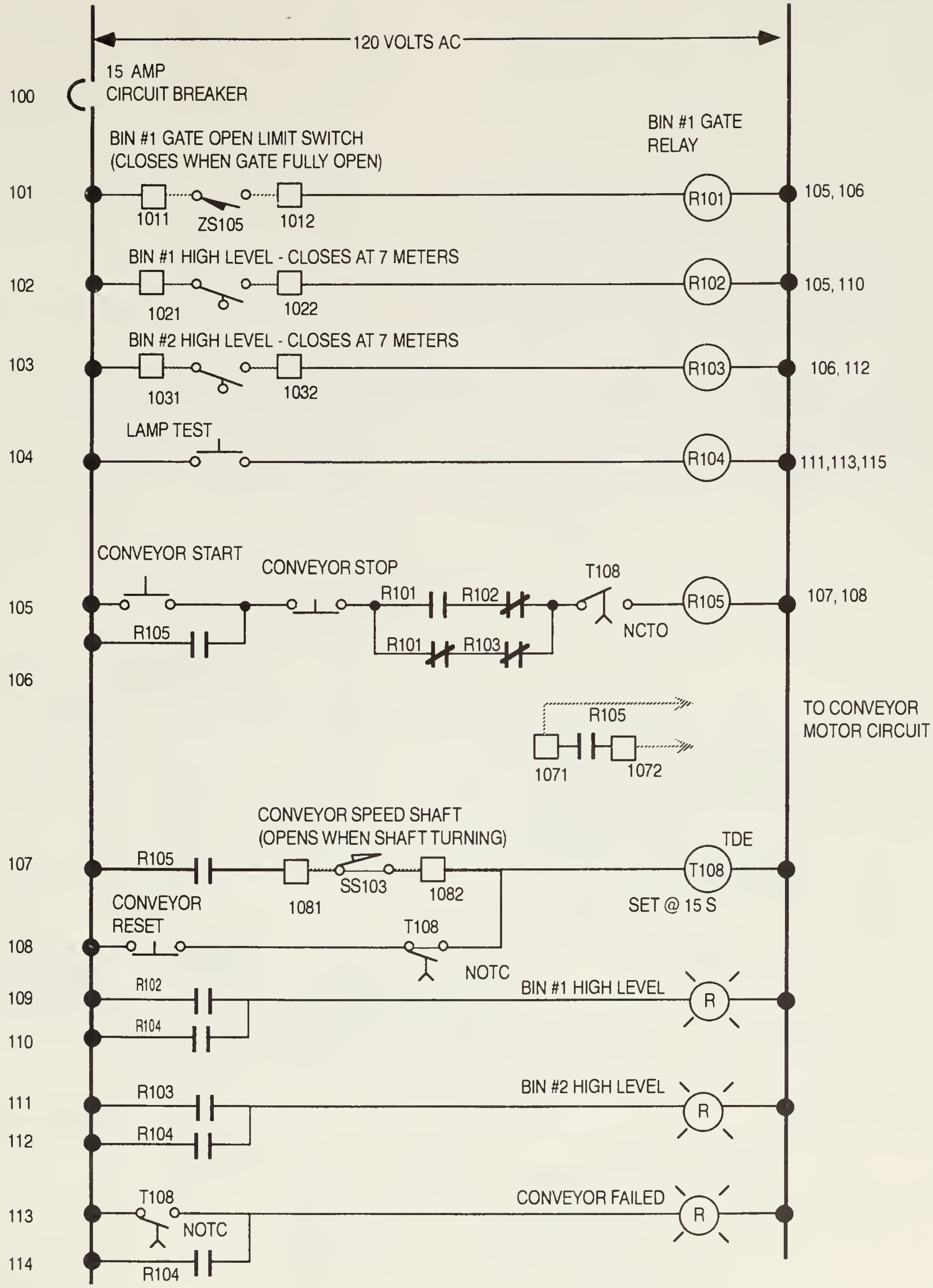

Fig. 12. Conveyor control system schematic diagram.

The timer, on line 108, does not operate its contacts for 15 s after its coil energizes. Therefore relay R105 energizes, causing the conveyor motor to start through normally open contact R105 on line 108. As R105 relay energizes, the normally open contact R105 on line 106 closes. This closure initiates the same action as the start button, so when the start button is released relay R105 supplies power to its own coil until the circuit is broken by any of the other elements in line 105 or line 106.

Timer T108 begins to time the events unless the conveyor belt speed switch opens to indicate the belt is operating. Should the speed switch fail to actuate, T108 stops timing 15 s after the conveyor motor starts. This action opens the normally closed T108 contact in line 105 and interrupts power to the coil of relay R105.

At the same time, the normally open T108 contacts on lines 109 and 114 close. Consequently, power is still supplied to the time delay element T108 on line 108 and the 'Conveyor Failed' red lamp on line 114 lights. T108 remains energized until the normally closed reset push button on line 109 is pressed, allowing the conveyor motor to be restarted.

Three other events also stop the conveyor motor. If the gate on bin 1 is open and the level in the bin is high, the relay R105 de-energizes when contact R102 opens on line 105. Secondly, if the gate on bin 1 is not open and there is a high level in bin 2, relay R105 de-energizes when contact R103 opens on line 106. Finally, if the stop button is pressed, power to the circuit is interrupted and R105 de-energizes. Note that although the start button is no longer pressed, R105 does not re-energize after the stop button is released because contact R105 on line 106 is no longer closed after relay R105 de-energizes. The circuit on line 114 operates the 'Conveyor Failed' alarm light.

Pressing the lamp test button on line 104 operates relay R104. This action causes both the 'High Level' lamps and the 'Conveyor Failed' lamp to illuminate with the R104 contacts on lines 111, 113, and 115.

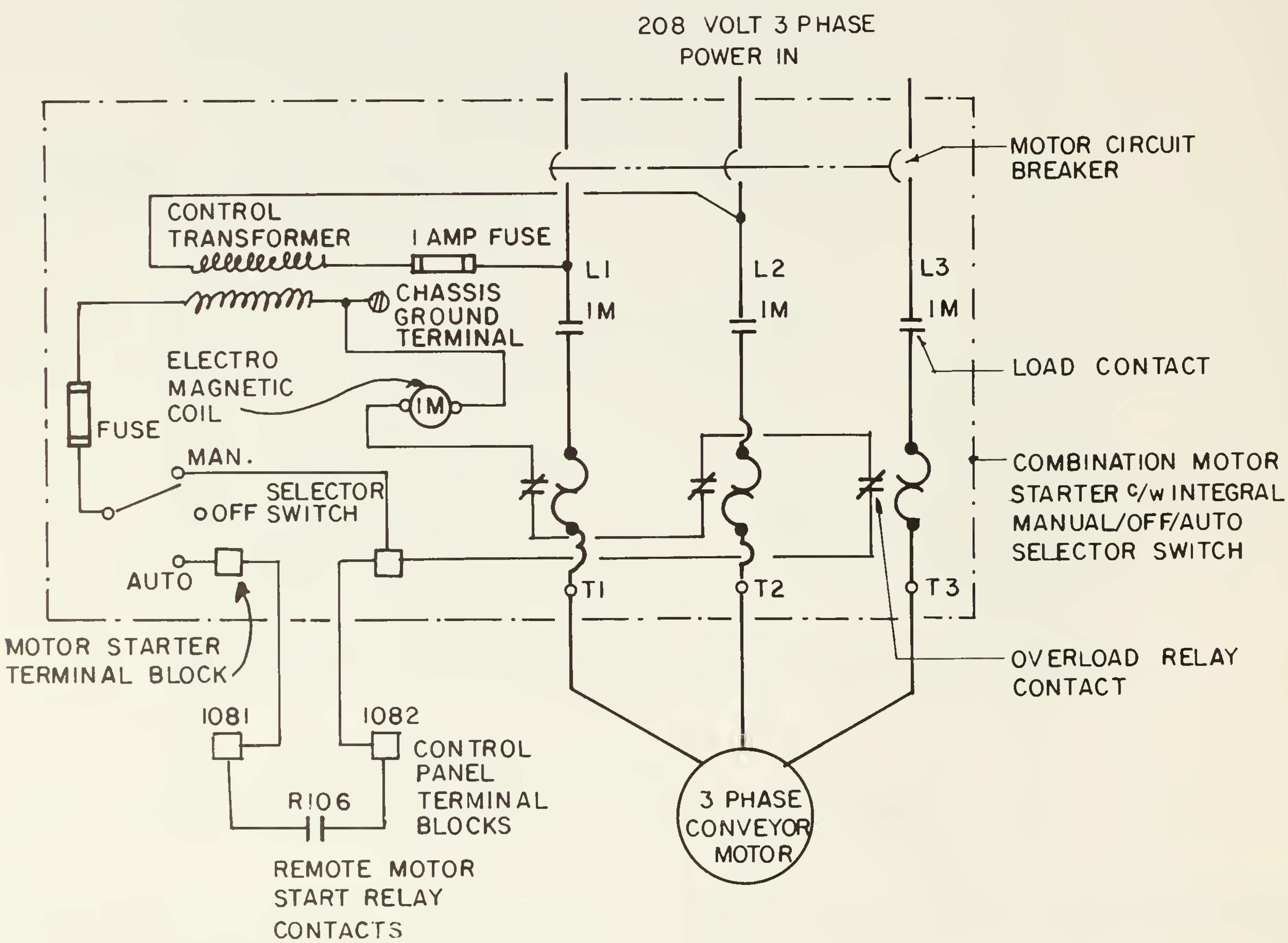

Fig. 13. Motor starter wiring diagram.

8.3 **Wiring diagrams**

Wiring diagrams are pictorial diagrams that show the actual wiring routes and connections of the devices in a control system. These diagrams usually follow from the ladder diagrams. Some designers use only wiring diagrams, particularly in heating and ventilation systems or in simple packaged control systems (e.g. appliances and motor control centres).

Fig. 13 illustrates a wiring diagram for the simple conveyor-motor starter (Fig. 11). For comparison, the schematic diagram of the same motor-starter circuit appears in Fig. 14.

8.4 **Loop diagrams**

Loop diagrams show the wiring of analog control systems. These diagrams combine the features of schematic and wiring diagrams. The loop diagram shows all the components in a pictorial format but portrays the interconnections merely schematically, rather than showing actual wiring routes. Use loop diagrams, for example, to show the wiring for programmable controller input and output signals because the controller-programming terminal produces the actual logic diagrams.

Other typical uses for loop diagrams include temperature control and temperature monitoring.

8.5 *Temperature control loop* The mechanical and loop diagrams, shown in Figs. 15 and 16, respectively, illustrate the control of air temperature in a ventilation system. Temperature control results from mixing outdoor air with return air. The temperature controller and damper operator are the electromechanical modulating control devices. A potentiometer adjusts the minimum amount of outside air brought into the system.

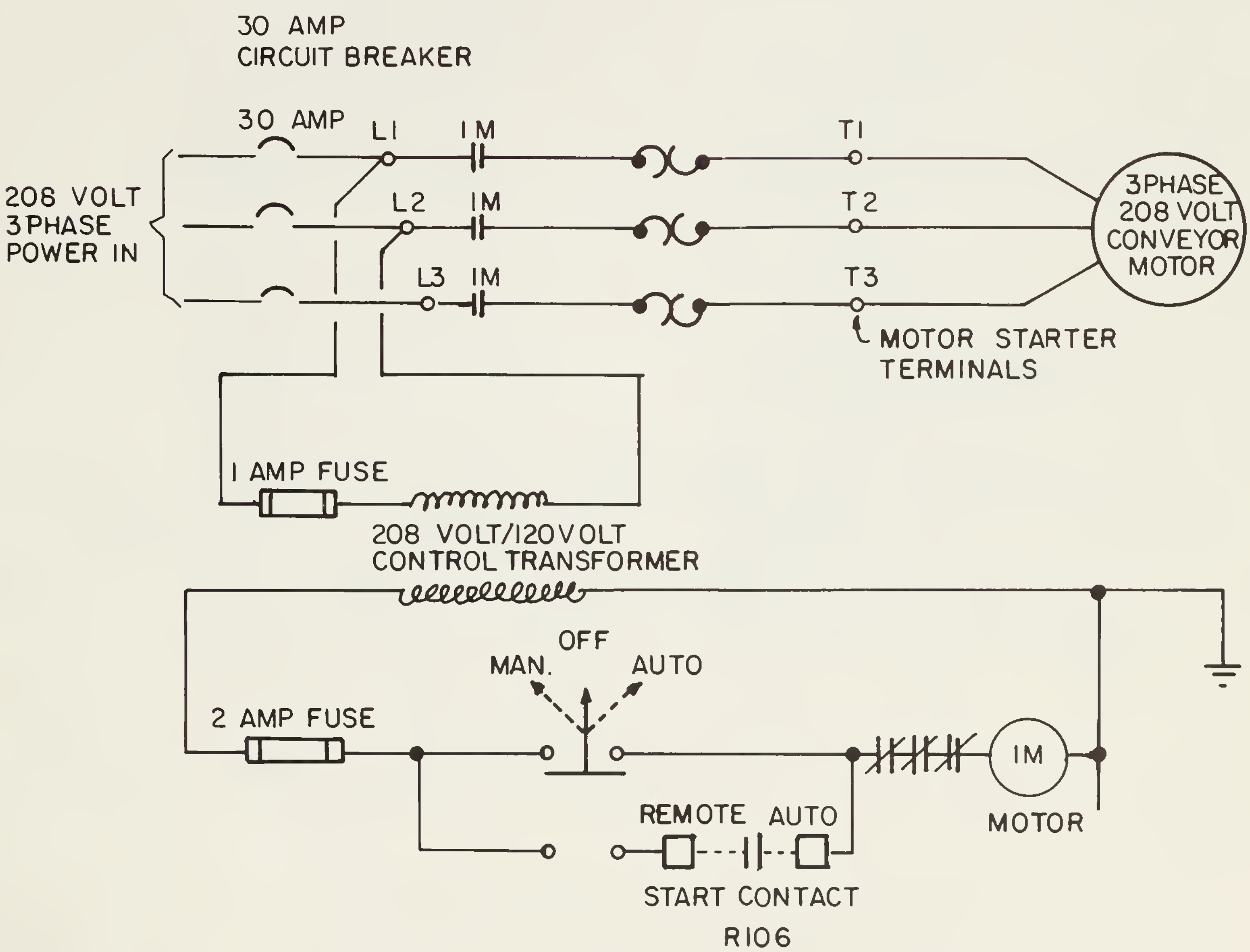

Fig. 14. Motor starter schematic diagram.

8.6 *Bin temperature monitoring system* This system (Figs. 17 and 18) monitors bin temperatures and sounds an alarm on high rates of temperature rise and on high absolute temperatures in each bin. The temperature sensors connect to a programmable controller through a common resistance-to-current signal conditioner. The programmable controller automatically selects a bin temperature sensor by energizing a relay that connects the sensor to the signal conditioner. The control program scans each sensor and determines the alarm status for each bin.

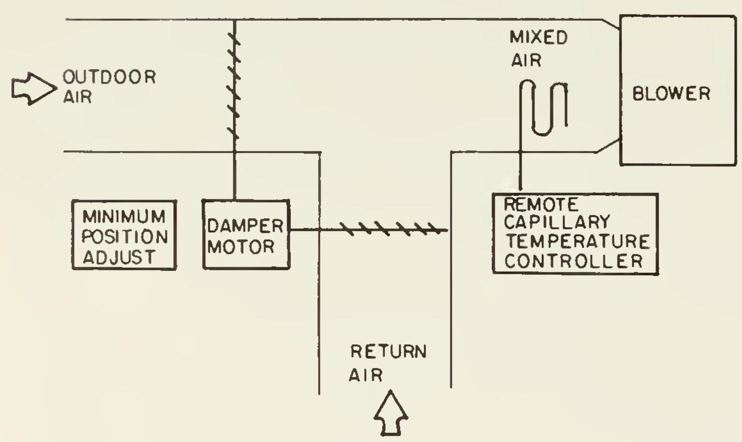

Fig. 15. Blower mechanical arrangement.

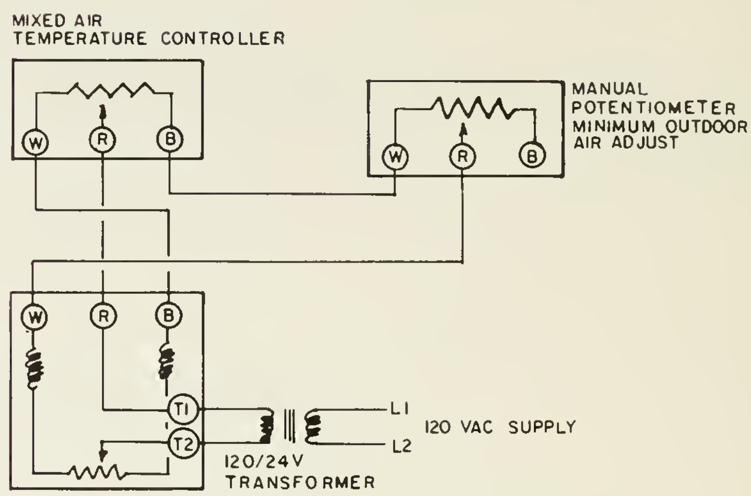

Fig. 16. Blower loop diagram.

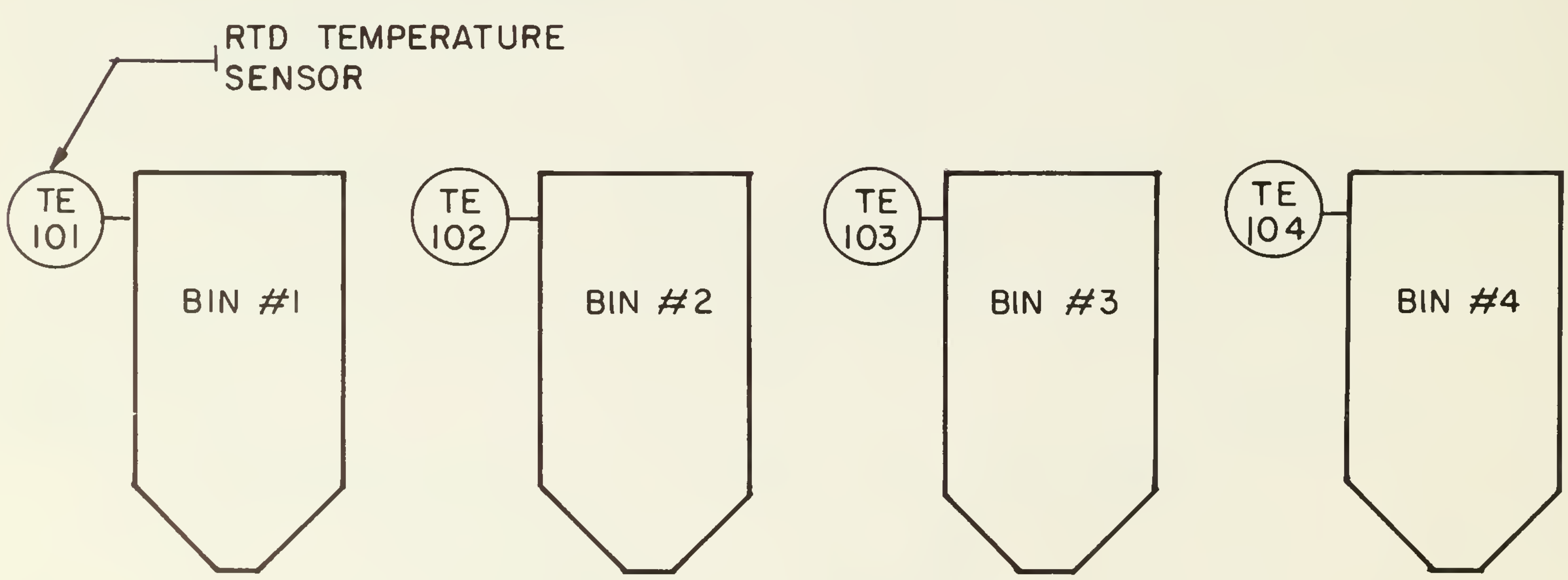

Fig. 17. Mechanical arrangement of bins in a system to monitor bin temperature.

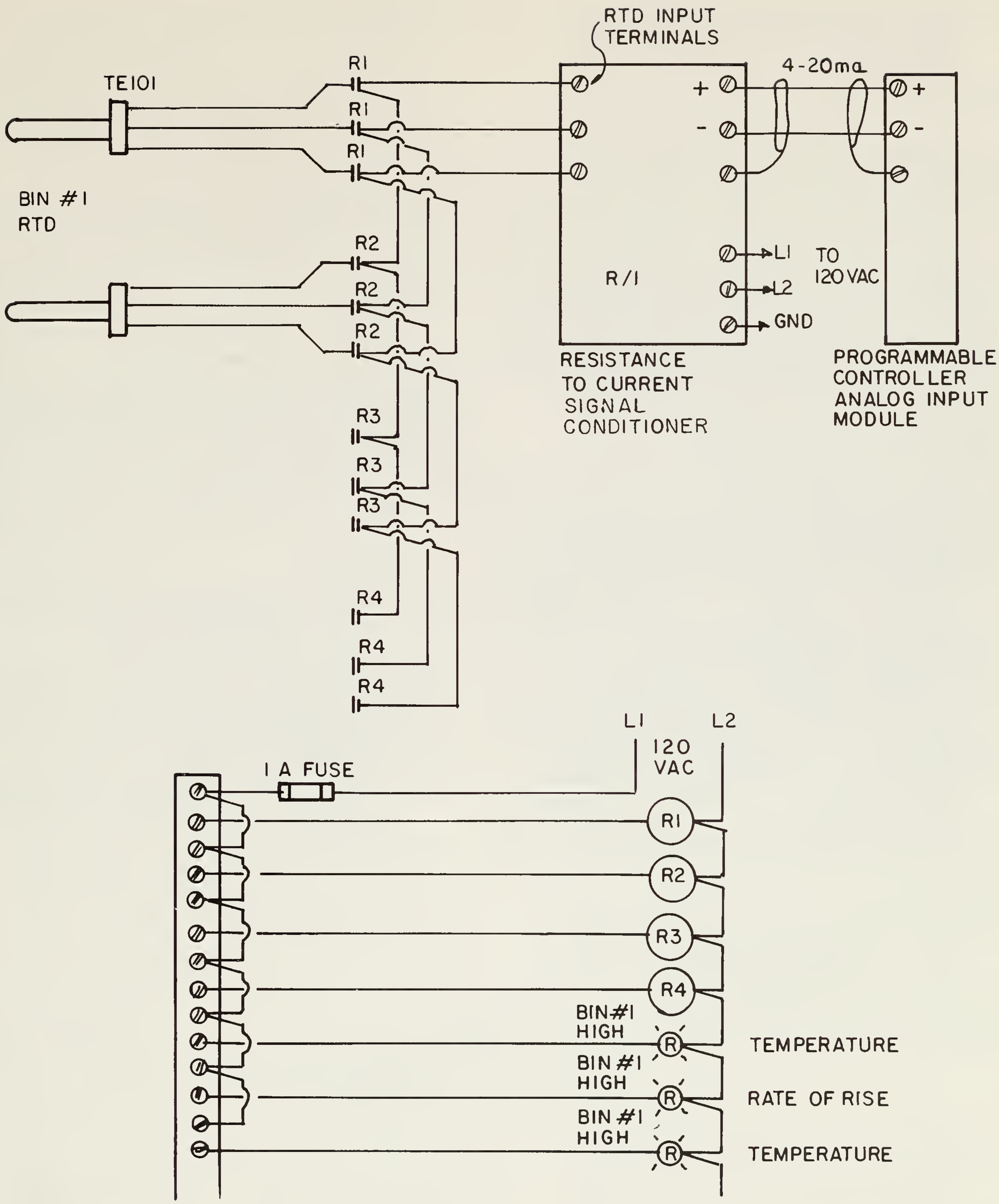

Fig. 18. Bin temperature monitoring system loop diagram.

9 SAMPLE PROBLEM: FEED STORAGE AND PROCESSING CENTRE

This sample design for a storage and processing centre for feed on a farm demonstrates the various principles discussed in this manual. The example does not provide a finished design, but rather illustrates the various mechanisms and processes that design of a control system entails. As well, this example shows the relationships that must be established between the process designers, the control system designers, and the system users in order to develop a successful system.

9.1 Process description

This facility includes four primary storage bins, numbered 1–4. Sensing devices to measure grain temperature and an aeration fan equip each bin. A screw conveyor mounted on top of the bins fills them. The bins discharge via central unloading conveyors to a reclaim conveyor, which discharges into a bucket elevator. This is leg 1 of the process.

Leg 1 discharges into a distributor that directs grain to the four storage bins, to the filling conveyor, to the truck loading area, to ingredient-storage bins (numbered 10–14), to a wet storage bin, or to a continuous-flow grain dryer. Level sensors in the ingredient-storage bins indicate the levels of accumulating grain, and electrically controlled slide gates control the discharges.

The ingredient bins discharge into a proportional grinder–mixer (PGM). The PGM discharges, via a pneumatic conveyor, to storage bins for the finished product, numbered 20–28. These storage bins are also equipped with high-level sensors.

The storage bin containing wet products discharges, via a screw conveyor, to the continuous-flow grain dryer. The dryer discharges into a second bucket elevator (leg 2), which in turn either discharges to the screw conveyor for the primary storage bin or recycles back to the grain dryer.

Fig. 19 illustrates the schematic diagram for equipment in this process, which relies on a programmable logic controller (PLC).

9.2 Control system design

Consider these objectives and requirements for the system:

- automatic start of the aeration fans in the primary storage bins if temperatures rise above a preset level (e.g. 25°C)
- automatic shutdown of the fans and illumination of alarms with status indication at temperatures above a specified level (e.g. 40°C)
- on any alarm, automatic time-delayed shutdown of the process from information from level sensors

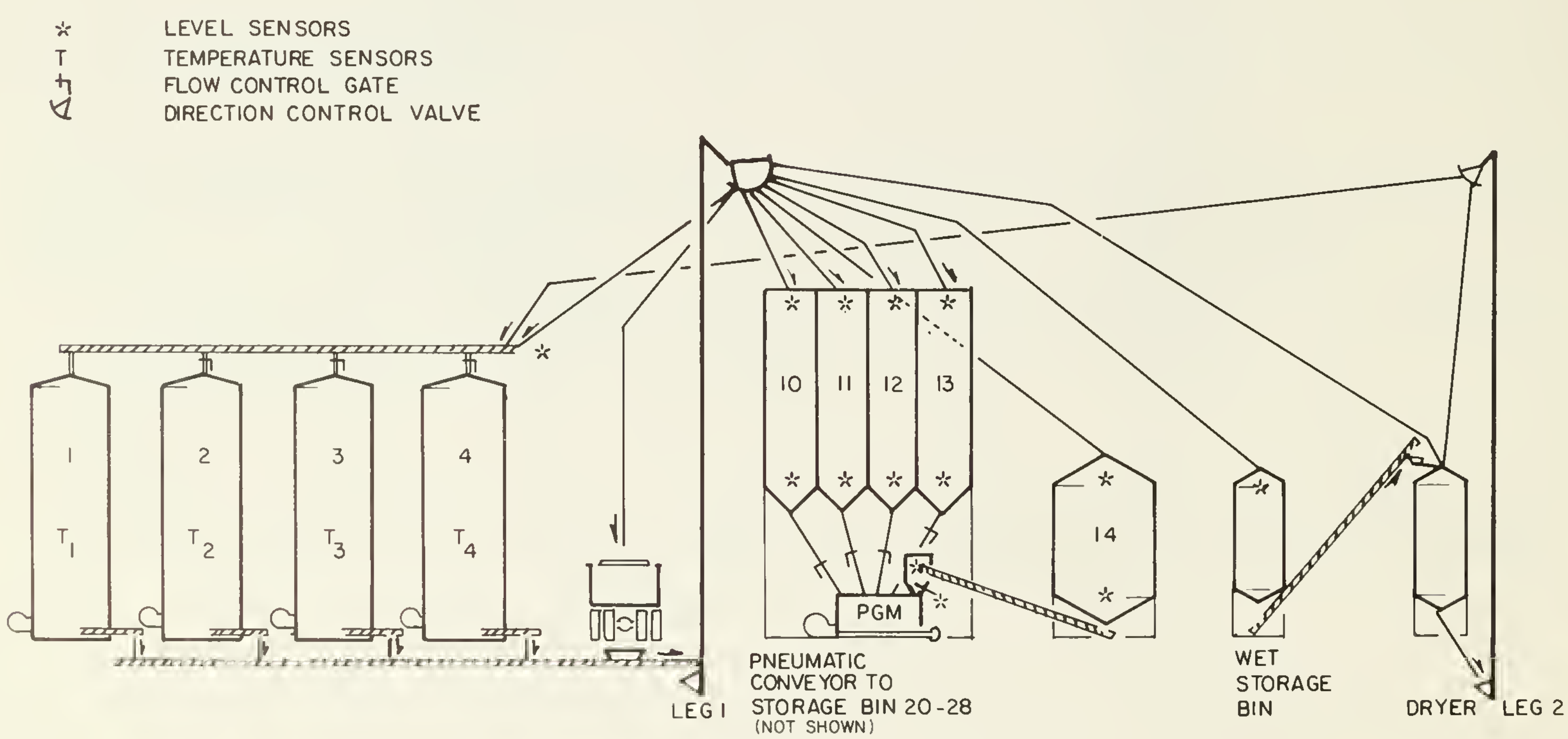

Fig. 19. Equipment layout schematic diagram for feed storage and processing centre.

- electrical load limiting by allowing only two of the dryer, bucket elevators, or PGM to operate at one time
- timed operation of the PGM before automatic sequential shutdown

9.3 *Defining system needs* The schematic diagram showing the mechanical layout, called the process diagram, is an essential element in defining system needs. On the process diagram schematically show all the controlled devices and the main process elements involved in the system, for example motors, gates, solenoid valves, bins, and conveyors. Use this diagram to detail the system's operation.

This process of determining how the control system operates is iterative and requires considerable interaction between the designers of the process and the control systems. Following are some examples of the items that the designers should determine at this conceptual design stage.

- size of bins
- size of motors
- electrical service limitations, i.e. which motors can run concurrently
- need for continuous level measurements, as opposed to specific elevation level switches
- need for continuous temperature measurement, i.e. is a simple fixed-point temperature alarm required or are rate-of-rise and readily adjustable temperature alarm settings necessary?
- environmental conditions under which the main control system must operate, i.e. dusty, clean, hot, or otherwise
- future needs for expansion of the system, i.e. is there a future need for more bins, valves, gates, or motors?
- budget restraints, i.e. how much automation is affordable?
- consequences of equipment shutdown, i.e. how rugged must the control system components be?
- accuracy and repeatability required in measuring the process variables such as product temperature, motor current, product weight, belt or conveyor speed, and bin level
- whether the operation is to be attended or unattended
- degree of manual intervention in the operation of the system
- whether the inventory control is to be automated or manual
- action to be taken after power failure, i.e. should the system restart automatically or wait for manual intervention?
- elements needed for measurement or control, e.g. bucket elevator speed, motor currents, or gate position
- allowable limits for the measured variables such as absolute temperature, rate of temperature rise, motor current, and elevator speed

As each input to the control system is identified, locate it on the process diagram. When this drawing is complete, it should contain both the measurement and the control devices. In some process industries, designers expand these drawings to show the interaction between the various pieces of control equipment. Such drawings are called process and instrumentation drawings (P and IDs). However, it would be difficult to show this degree of detail for the control of a storage and processing centre for feed, with its multiple combinations of control points. Therefore, in this example, we show only the devices themselves.

Even though a complete P and ID is not produced, some of the conventions used in producing this kind of diagram do apply. Refer to the manuals published by the Instrumentation Society of America for detailed information on the numbering schemes and symbols used in producing P and IDs.

At this stage of the design, the nuances of system operation are almost impossible to convey in writing without a great deal of effort. Verbal communication is the most effective means of conveying to the user the intent of the design. Keep lines of communication open.

9.4 *Interface of user and machine* The user is crucial to the smooth operation of any automated facility. During the design phase, determine the user's preference on the following points:

- central or dispersed control of the facility
- traditional operator interface (e.g. lights and push buttons) or microcomputer interface
- level of sophistication, i.e. a sophisticated operation adapts easily to a microcomputer interface and can take advantage of the greater flexibility
- method of setting control points, i.e. if the operator uses a programmable controller, these points can be set with the controller programming console

Designing the interface of user and machine is best done through discussions with the operators of the facility. Involve them in the design decisions, when possible.

9.5 *Control sequence description* Several methods exist to identify the entire operational control sequences, but the most effective of these is the spreadsheet format.

In the spreadsheet format, each sequence of operation in the subsystem appears as a series of stages heading a row of columns. Each of the controlled items, with the delay between one operation and the next, follows in the appropriate column. If a subsystem forms part of the operating sequence of another subsystem (e.g. dust collection), show the subsystem in the appropriate column in the same way as you would a controlled device.

In addition, show the start-up and shutdown sequences along with the stage where these sequences would go in the event of an abnormal condition.

This sample problem—the storage and processing centre for feed on a farm—requires a controlled shutdown of materials transfer if a high-level switch activates in an ingredient bin. The discharge-unloading conveyor in the primary storage bin deactivates first. After a time delay, to allow the reclaim conveyor to empty, it stops. Following another time delay, the bucket elevator stops.

If a plugged spout in the distributor causes a problem, a different shutdown sequence would take place. In this event, there is no time to empty the various conveyors. Therefore all the controlled elements would stop simultaneously. A spreadsheet can easily illustrate the sequences of these events.

More than merely illustration, the spreadsheet allows the control system designer to convey the system requirements to the process designer. In addition, after the system is designed, the spreadsheet serves as an operations manual to show the operator how the various control sequences work.

As the spreadsheet is developed, consider the following elements of the design.

- In what order should each component start and stop, for both normal and abnormal sequences?
- What are the interstage delay time settings?
- What events should occur after a power failure?
- What are the settings for the various sensing devices? For example, at what temperature should the bin ventilation fans start?
- What are the current ranges for the motors?
- Over what range should the analog transmitters operate, e.g. if a transmitter of 4–20 mA is used, what temperature would 4 mA represent?

As each of the above questions is answered, the information can be included in the P and ID. When this stage of the design is complete, the control-system designer should have all the information necessary to complete the design.

9.6 *Logic flow diagram* If the designer produces a spreadsheet, a logic flow diagram would not likely be required for the entire process. However, some particularly complex subsystem control sequences may warrant a flow diagram. As well, maintenance personnel unfamiliar with a large electrical control system may need the detail provided by a logic flow diagram to understand the system.

At this point in the design, all the information necessary to produce a complete design should be in place.

9.7 *Selecting components* The control-system designer, working with the mechanical-equipment designer, selects the control equipment. Take care to ensure that each piece of equipment operates exactly as required. Two examples: If the design specifies that a gate limit switch is needed to indicate that a gate is open, the switch must not operate until the gate is fully open. If it is important to know whether a gate is open or closed, include two switches.

Often mechanical equipment comes with its own sensors and controlled devices, e.g. solenoid valves. Clearly identify the exact operation of this auxiliary equipment. Many problems can arise in attempts to integrate equipment supplied by various manufacturers. If possible, specify the equipment manufacturer in the system design. Retrofitting compatible control equipment is sometimes better than using equipment supplied by a variety of companies.

Also at this stage in the design specify the type of control system. The feed storage and processing centre of this sample problem is best served by a programmable logic controller (PLC). List all the input and output signals to the PLC so you can estimate the memory size required for the application. After making allowances for future expansion, select the appropriate controller.

9.8 Schematic diagram

If conventional electromechanical controls are used, generate a schematic diagram. This diagram provides information on which to base the size of both the control panel and the

control room. Produce analog loop diagrams now as well.

Control systems relying on programmable controllers require only input/output loop diagrams at this stage. The software for the PLC can be generated any time later. In fact, it is often more efficient to generate the software after the system is constructed. Frequently the need to alter some aspect of the operation appears only during construction. In addition, programmers can develop PLC software more easily if the requirements for the program and system are nearly complete.

Document the ladder diagram produced by the PLC fully with cross references, descriptions of the various control sequences, control and measurement elements, and components affected. Many software packages can facilitate this exercise.

9.9 Control panel design

Consider the following questions when designing a control panel:

- What type of enclosure is required? For example, is the control panel in a dusty or humid environment?
- Is ventilation required because of high ambient temperatures?
- Is there enough space in the control panel to allow for future expansion?
- Will the conduits and wires enter from the top or bottom of the cabinet?
- Is there sufficient space to connect field wiring?
- Are the components in the panel readily accessible for maintenance?
- Are the control components, such as lights and push buttons, labeled? Ensure precise wording on labels.
- Are the components arranged logically? Group subsystem control components together.
- If a microcomputer is used for the interface of operator and machine, can the facility still be operated manually in the event of computer failure?

9.10 Conclusions

Designing a control system, even for a basic feed storage and processing centre, demands successful integration of the instruments for measurement and control with the mechanical equipment and the human operator. This manual stresses the importance of a totally integrated design and provides a guide to the benefits derived from a system designed this way.

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